# The radio-bright future of studying black holes

Maciek Wielgus
Black Hole Initiative Postdoctoral Fellow

Black Hole Initiative, Harvard University
Smithsonian Astrophysical Observatory

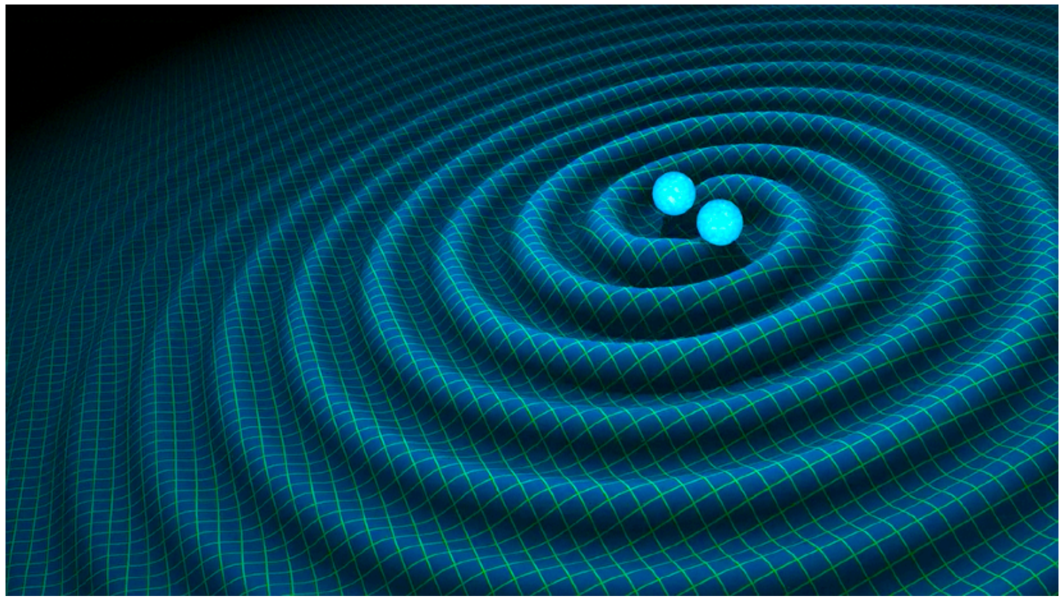
Event Horizon Telescope

Smithsonian

VE RI TAS
HARVARD

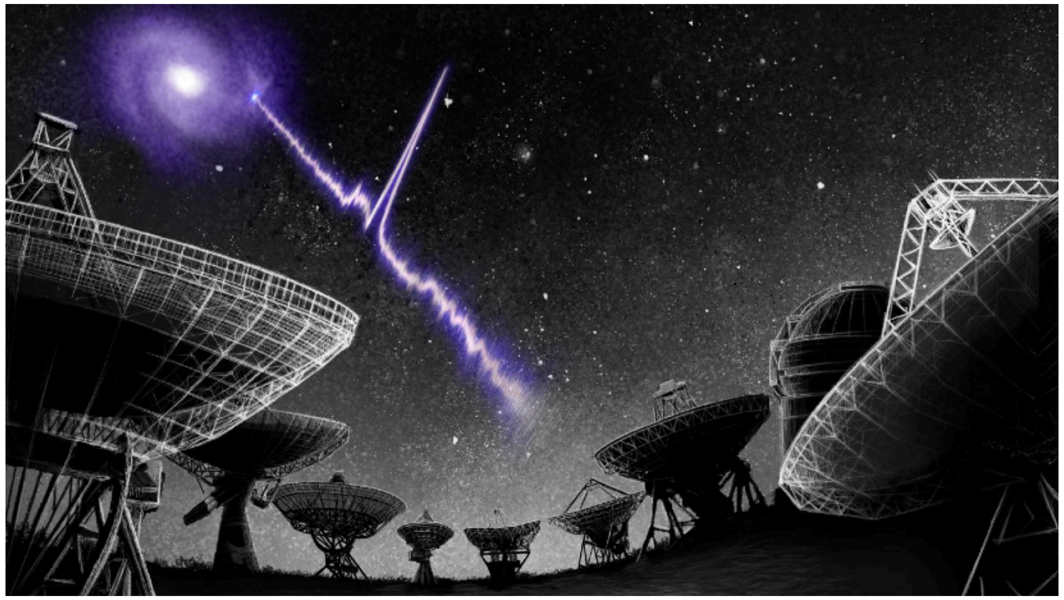
**Tsinghua University**
**11 Jan 2021**

# 2011-2020: an amazing decade in Astrophysics

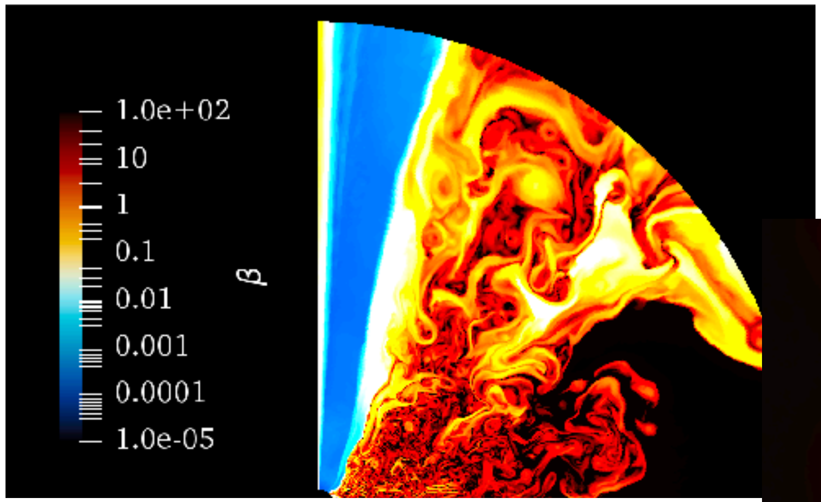


Gravitational waves, credit: NASA


Extrasolar planets,
credit: youtube



FRBs, credit: artsource.nl




GRMHD advances
credit: Bacchini et al.

Imaging black holes
credit: EHT

# Radiointerferometry

**Connected**

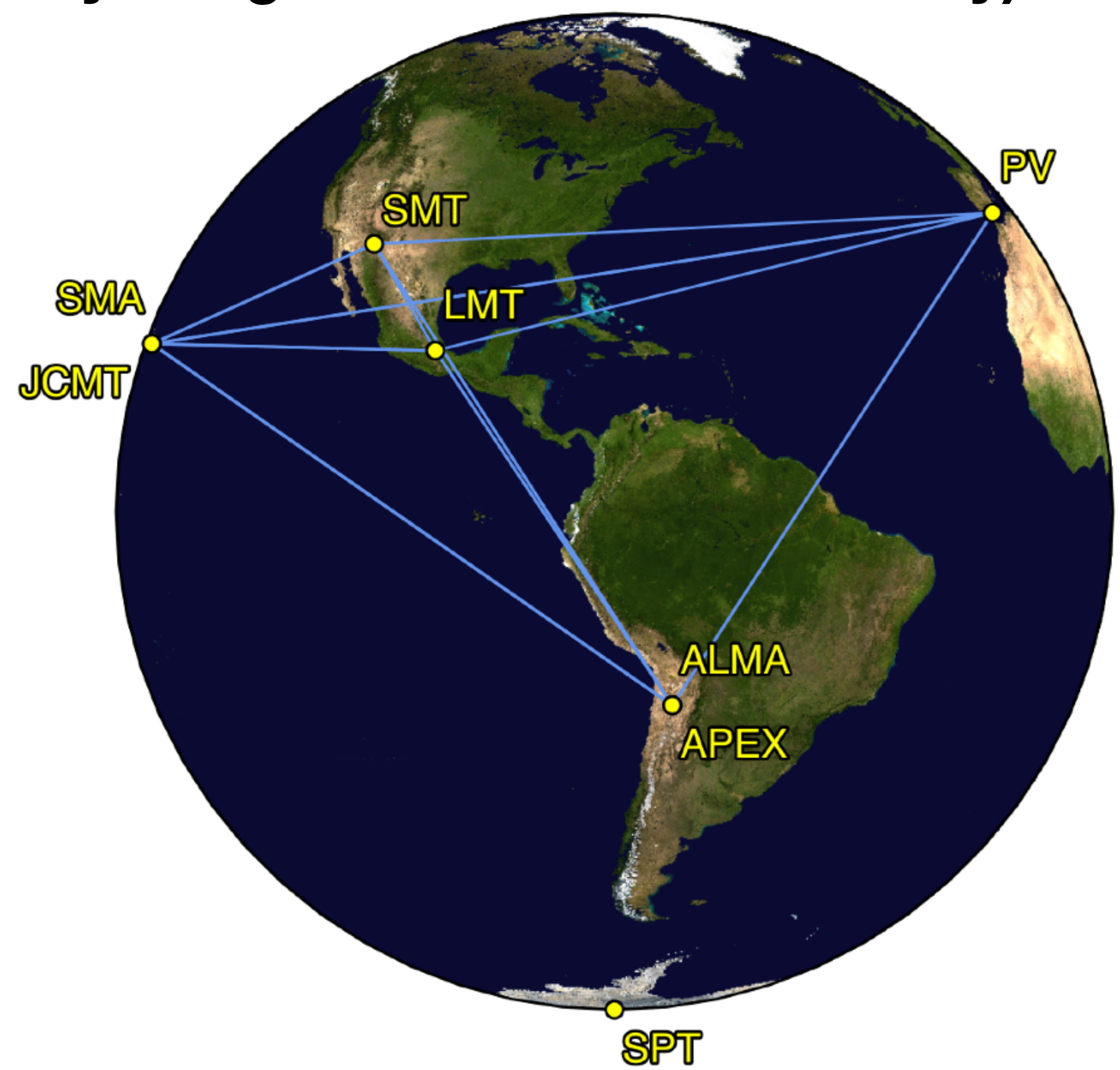
ALMA (credit: ESO)

# Radiointerferometry

**Connected**

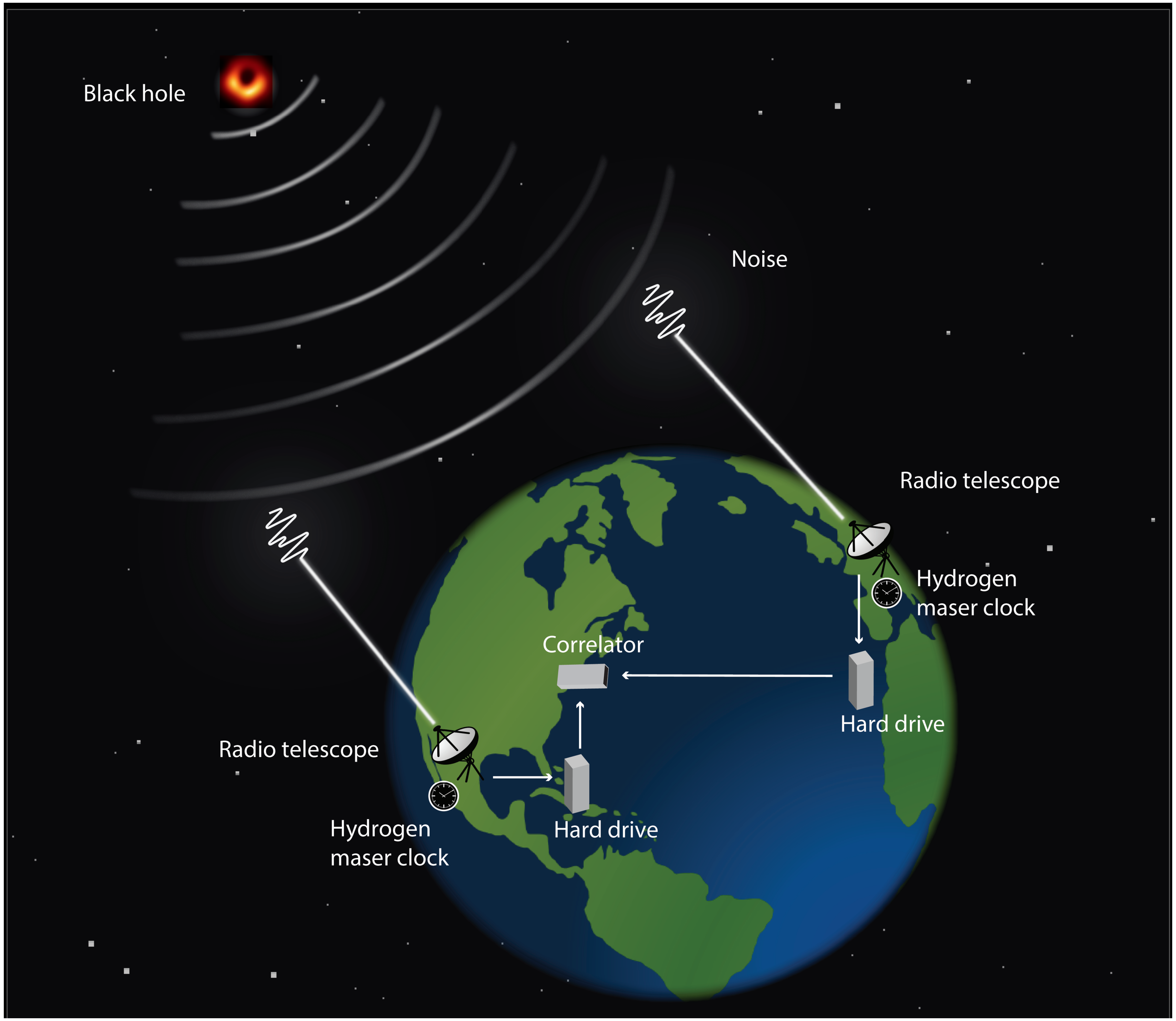
ALMA (credit: ESO)

**Remote**
**(Very Long Baseline Interferometry)**

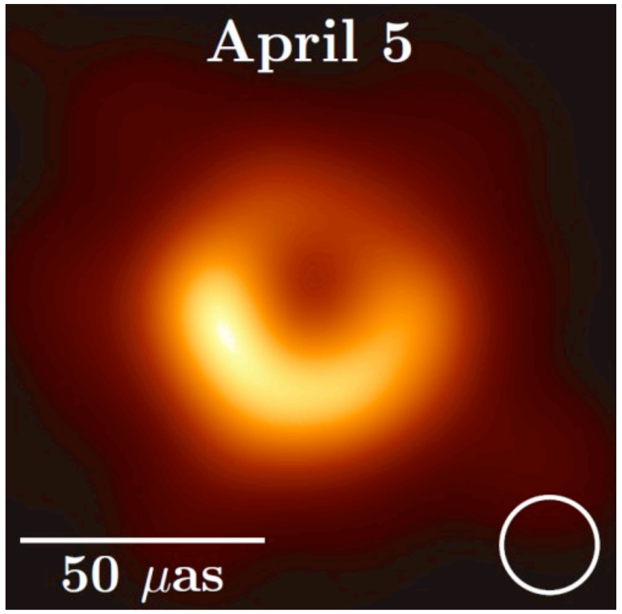



Event Horizon Telescope array in 2017

# Very Long Baseline Interferometry




$$\frac{\lambda}{D} = \frac{1\ \text{mm}}{10{,}000\ \text{km}} = 20\ \mu\text{as}$$



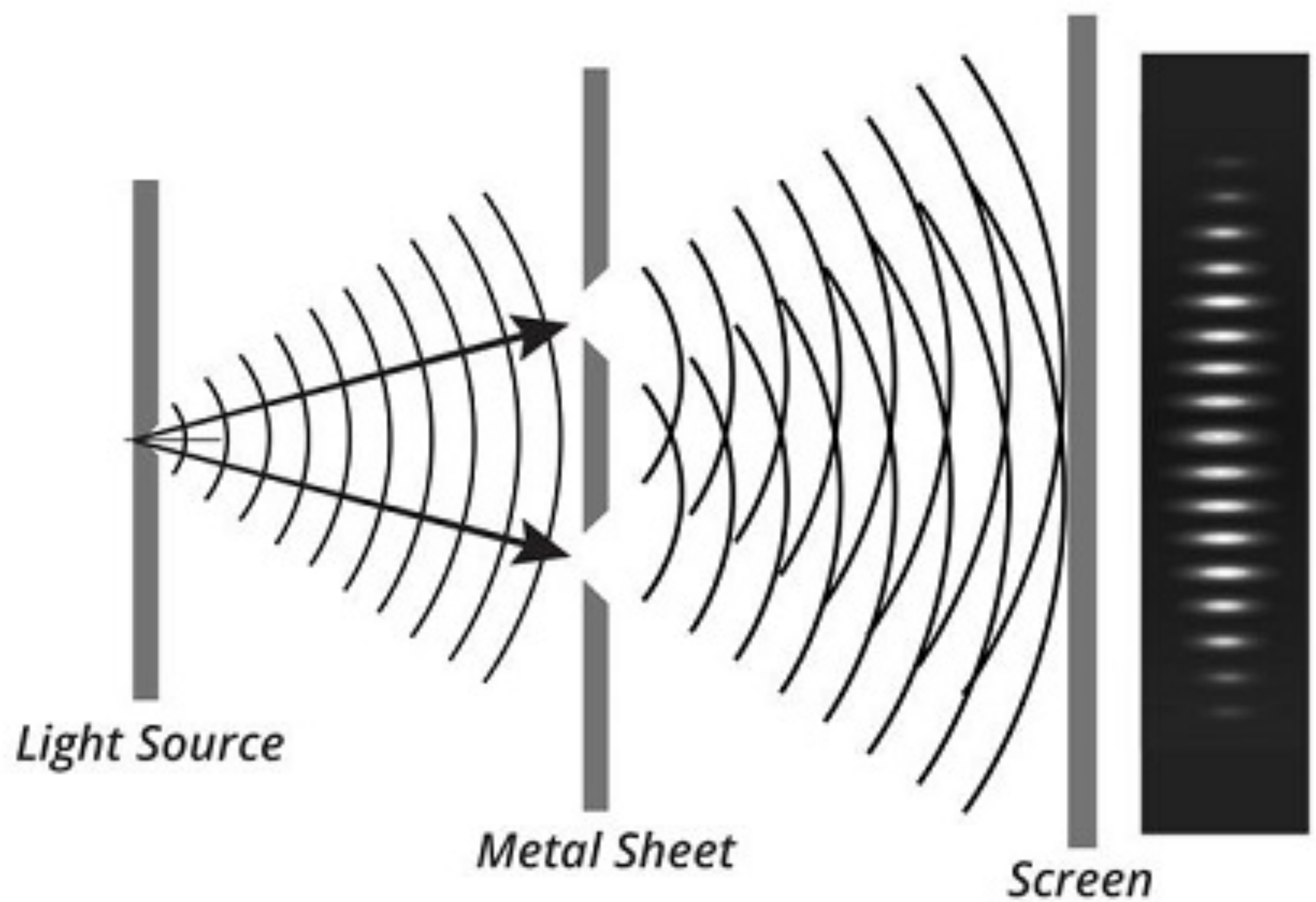

**EHT Resolution: ~20 μas**

**230 GHz ↔ 1.3 mm**

**M87**

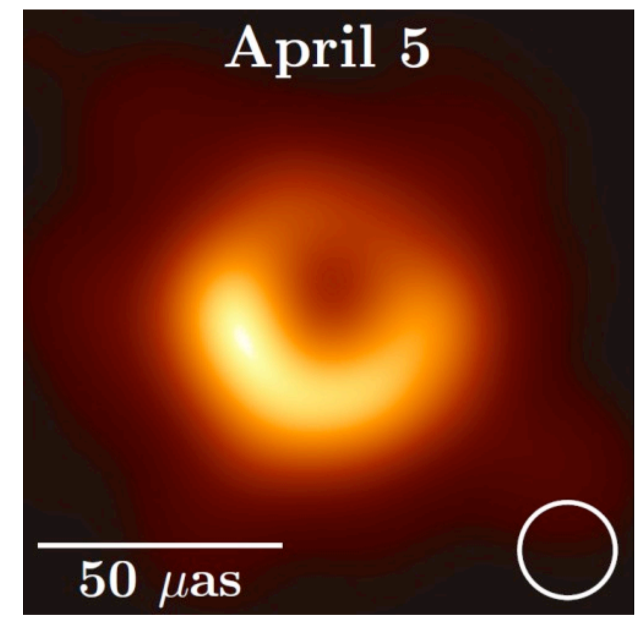
# Very Long Baseline Interferometry

**Double slit experiment**




**Fringe (interference) pattern**

$$\frac{\lambda}{D} = \frac{1\ \text{mm}}{10{,}000\ \text{km}} = 20\ \mu\text{as}$$




**EHT Resolution: ~20 μas**

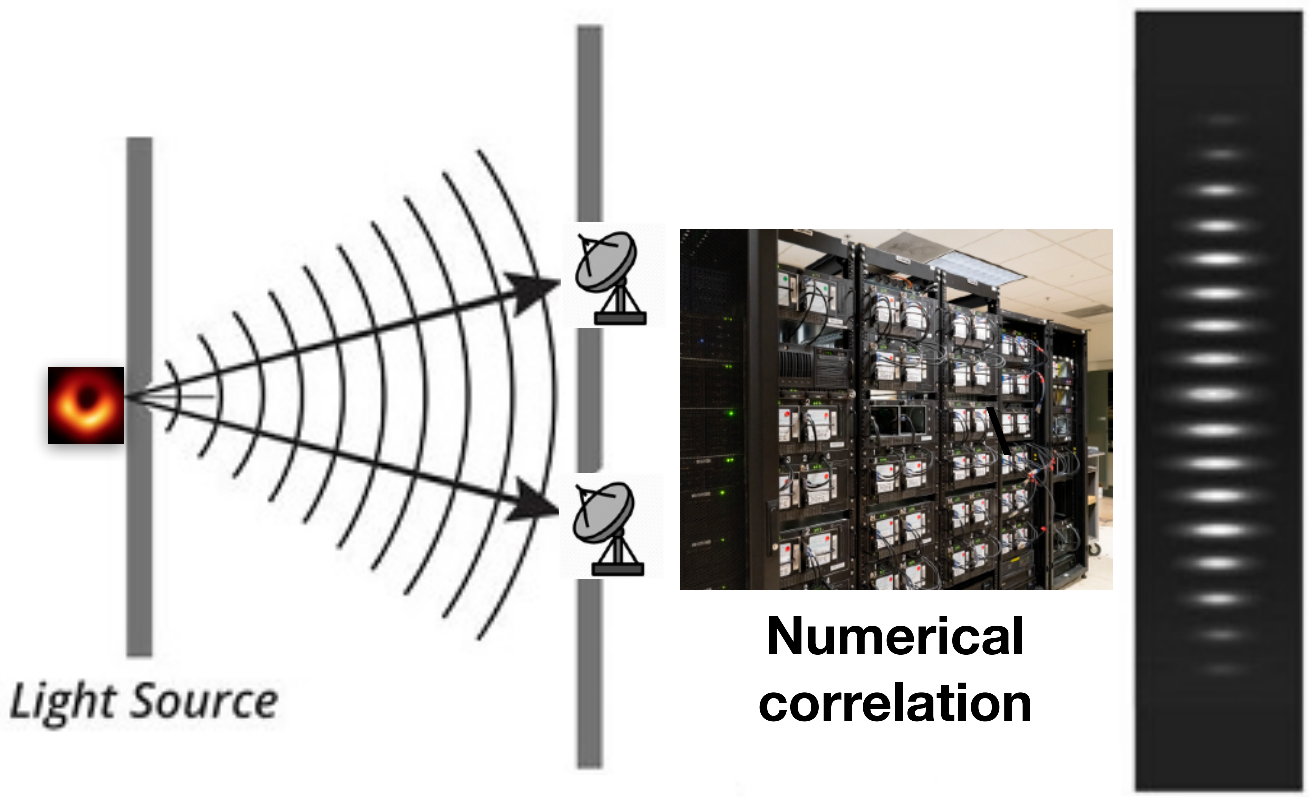
**230 GHz ↔ 1.3 mm**

**M87**

# Very Long Baseline Interferometry

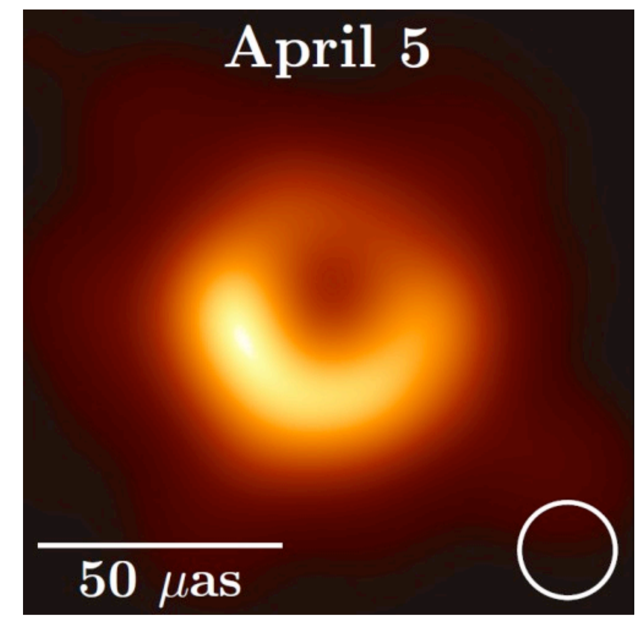
**Double slit experiment**

$$\frac{\lambda}{D} = \frac{1\ \text{mm}}{10{,}000\ \text{km}} = 20\ \mu\text{as}$$




**Numerical correlation**

**Fringe (interference) pattern**




**EHT Resolution: ~20 μas**

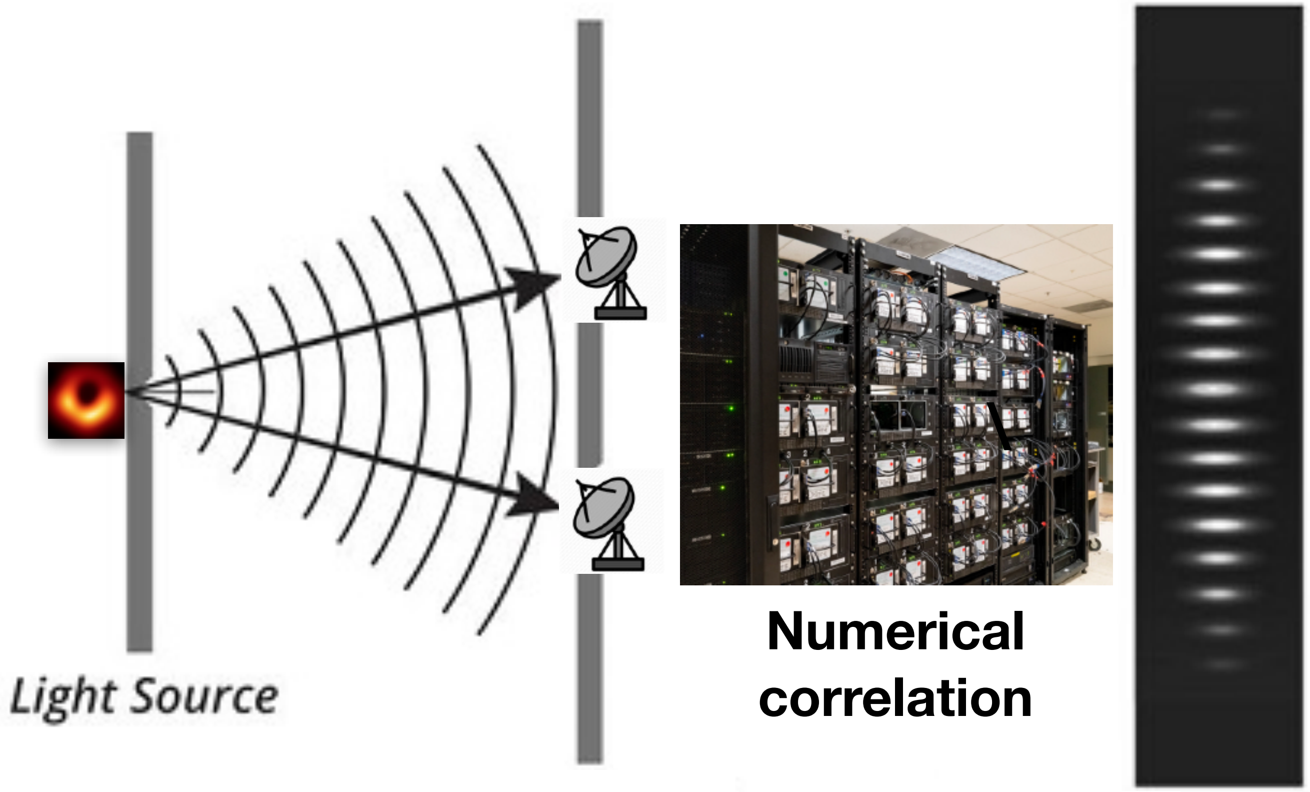
**230 GHz ↔ 1.3 mm**

**M87**

# Very Long Baseline Interferometry

**Double slit experiment**

$$\frac{\lambda}{D} = \frac{1\ \text{mm}}{10{,}000\ \text{km}} = 20\ \mu\text{as}$$

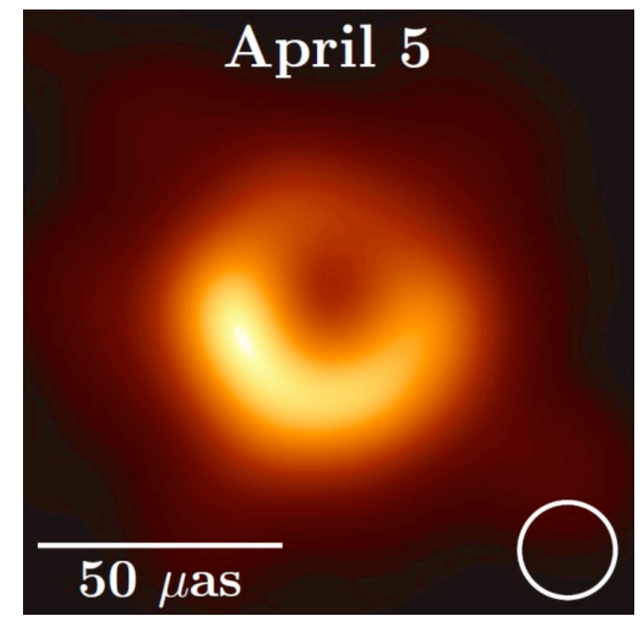



**Numerical correlation**

**Fringe (interference) pattern**

**FT**

**(van Cittert-Zernike)**



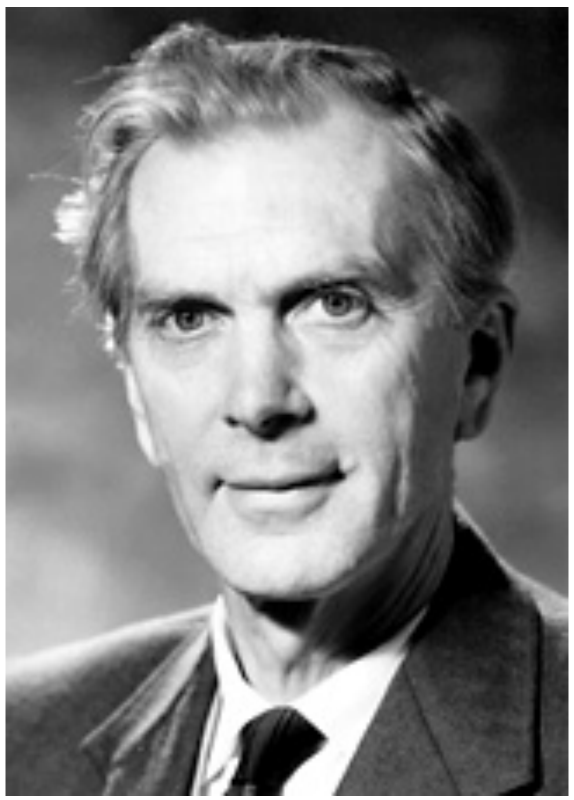

**EHT Resolution: ~20 μas**

**230 GHz ↔ 1.3 mm**

**M87**

Event Horizon Telescope

# Radiointerferometry and VLBI



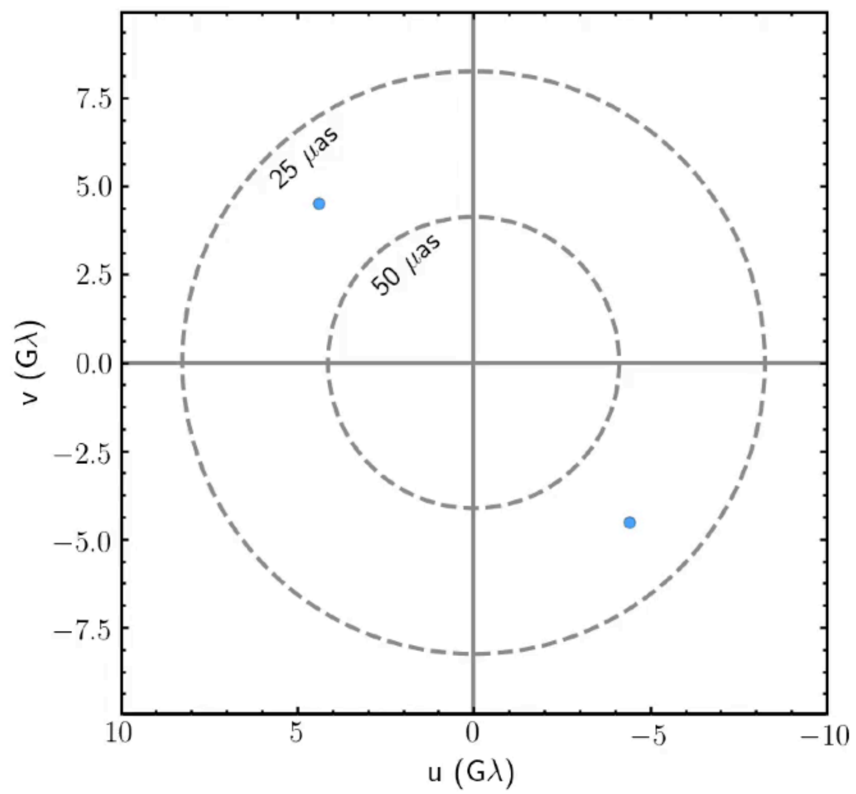
**Martin Ryle**
(1918-1984)

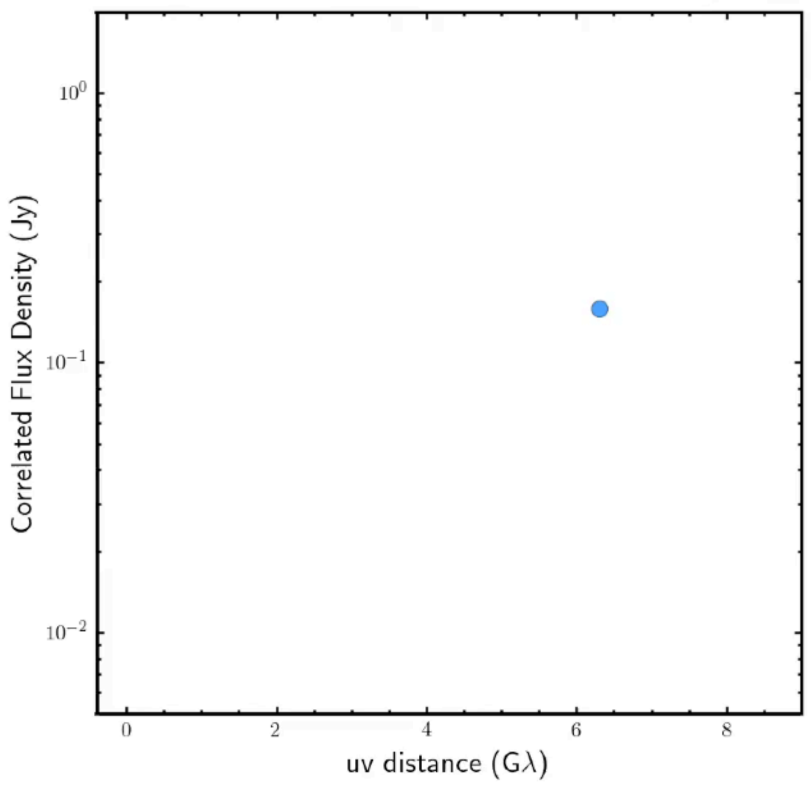

**Nobel Prize in Physics 1974**
for the pioneering research in radio astrophysics,
for his observations and inventions,
in particular of the **aperture synthesis** technique

# VLBI and the aperture synthesis

True story from the April 11th 2017

D. Palumbo & M. Wielgus



# Proto-EHT observations of M87* in 1.3 mm

A story based on Wielgus et al. + EHTC, ApJ 2020


**2009:** CARMA + SMT + JCMT

*Doeleman et al 2012* - compact core of M87

# Proto-EHT observations of M87* in 1.3 mm

A story based on Wielgus et al. + EHTC, ApJ 2020

Science AAAS

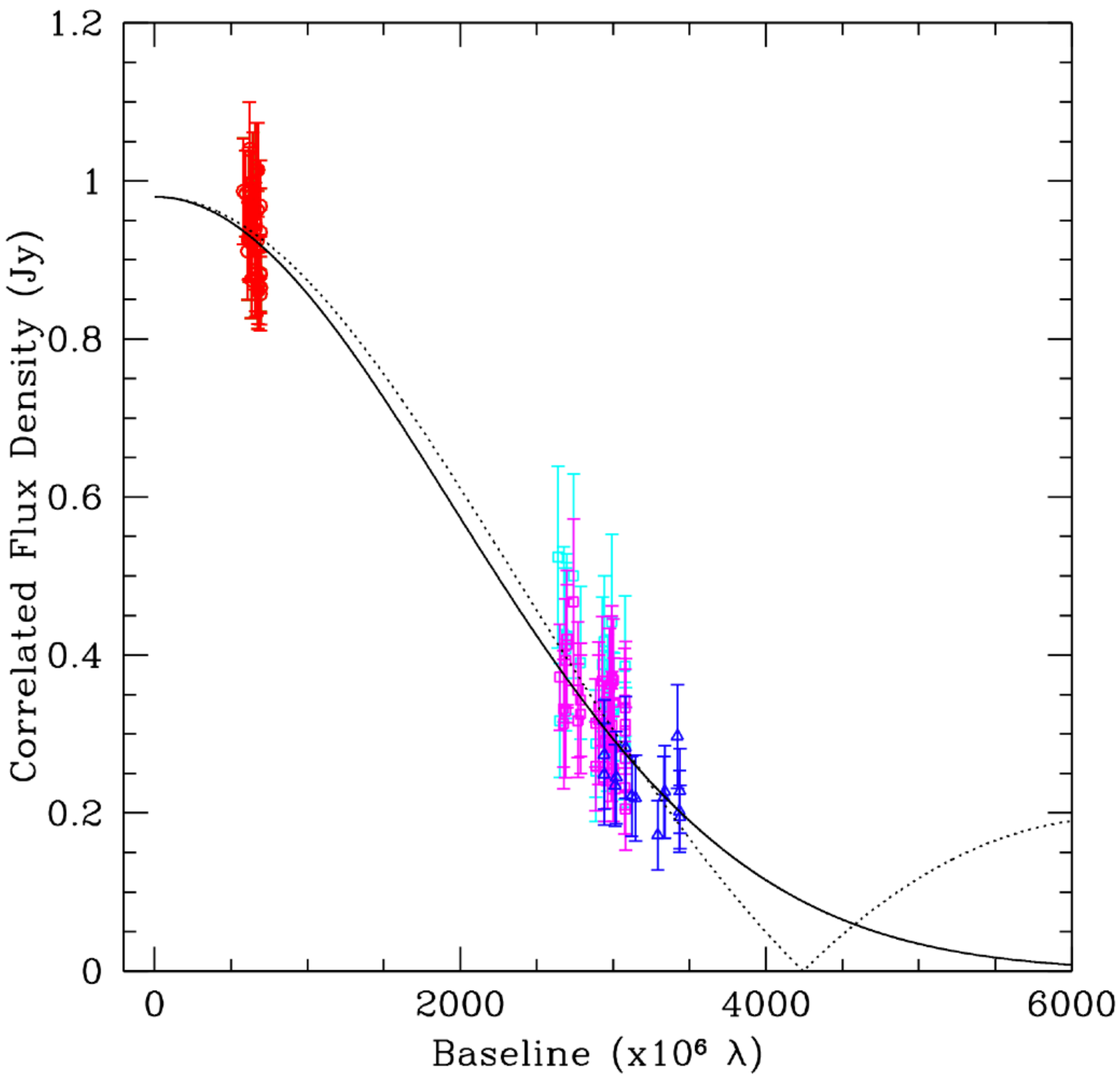
**Doeleman et al 2012**

**Jet Launching Structure Resolved Near the Supermassive Black Hole in M87**

Authors: **Sheperd S. Doeleman[1,3*], Vincent L. Fish[1], David E. Schenck[1,2†], Christopher Beaudoin[1], Ray Blundell[3], Geoffrey C. Bower[4], Avery E. Broderick[5,6], Richard Chamberlin[7], Robert Freund[2], Per Friberg[8], Mark A. Gurwell[3], Paul T. P. Ho[9], Mareki Honma[10,11], Makoto Inoue[9], Thomas P. Krichbaum[12], James Lamb[13], Abraham Loeb[3], Colin Lonsdale[1], Daniel P. Marrone[2], James M. Moran[3], Tomoaki Oyama[10], Richard Plambeck[4], Rurik A. Primiani[3], Alan E. E. Rogers[1], Daniel L. Smythe[1], Jason SooHoo[1], Peter Strittmatter[2], Remo P. J. Tilanus[8,14], Michael Titus[1], Jonathan Weintroub[3], Melvyn Wright[4], Ken H. Young[3], Lucy Ziurys[2]**

# Proto-EHT observations of M87* in 1.3 mm

A story based on Wielgus et al. + EHTC, ApJ 2020




**detections in 2009**

# Proto-EHT observations of M87* in 1.3 mm

A story based on Wielgus et al. + EHTC, ApJ 2020


**2009:** CARMA + SMT + JCMT
*Doeleman et al 2012* - compact core of M87

**2011:** CARMA + SMT + JCMT/SMA/CSO
*Data calibrated, not published*

# Proto-EHT observations of M87* in 1.3 mm

A story based on Wielgus et al. + EHTC, ApJ 2020


**2009:** CARMA + SMT + JCMT
*Doeleman et al 2012* - compact core of M87

**2011:** CARMA + SMT + JCMT/SMA/CSO
*Data calibrated, not published*

**2012:** CARMA + SMT + SMA
*Akiyama et al 2015* - first closure phases

# Proto-EHT observations of M87* in 1.3 mm

A story based on Wielgus et al. + EHTC, ApJ 2020

**Akiyama et al 2015**

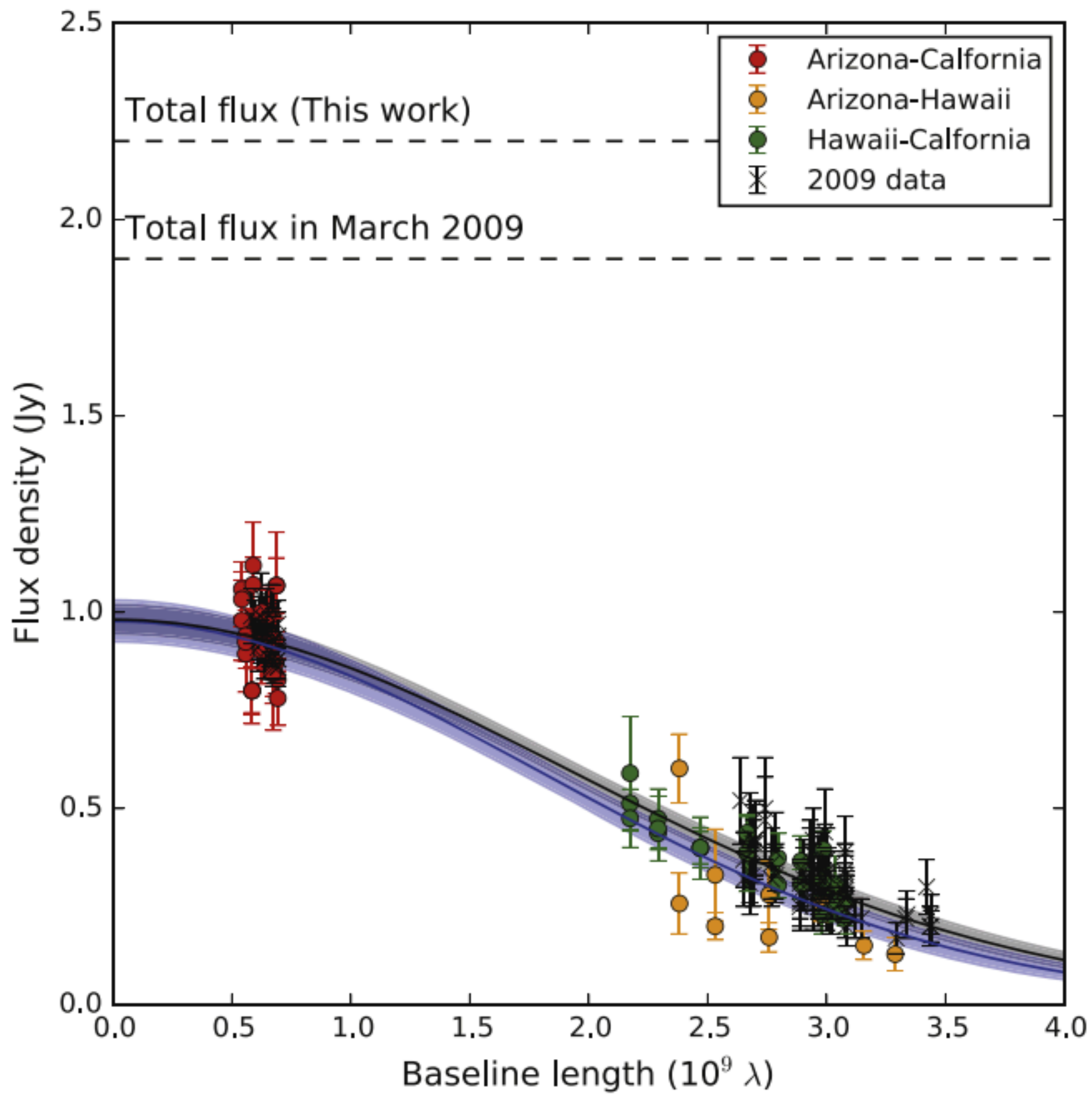
THE ASTROPHYSICAL JOURNAL, 807:150 (11pp), 2015 July 10
doi:10.1088/0004-637X/807/2/150


230 GHz VLBI OBSERVATIONS OF M87: EVENT-HORIZON-SCALE STRUCTURE DURING AN ENHANCED VERY-HIGH-ENERGY $\gamma$-RAY STATE IN 2012

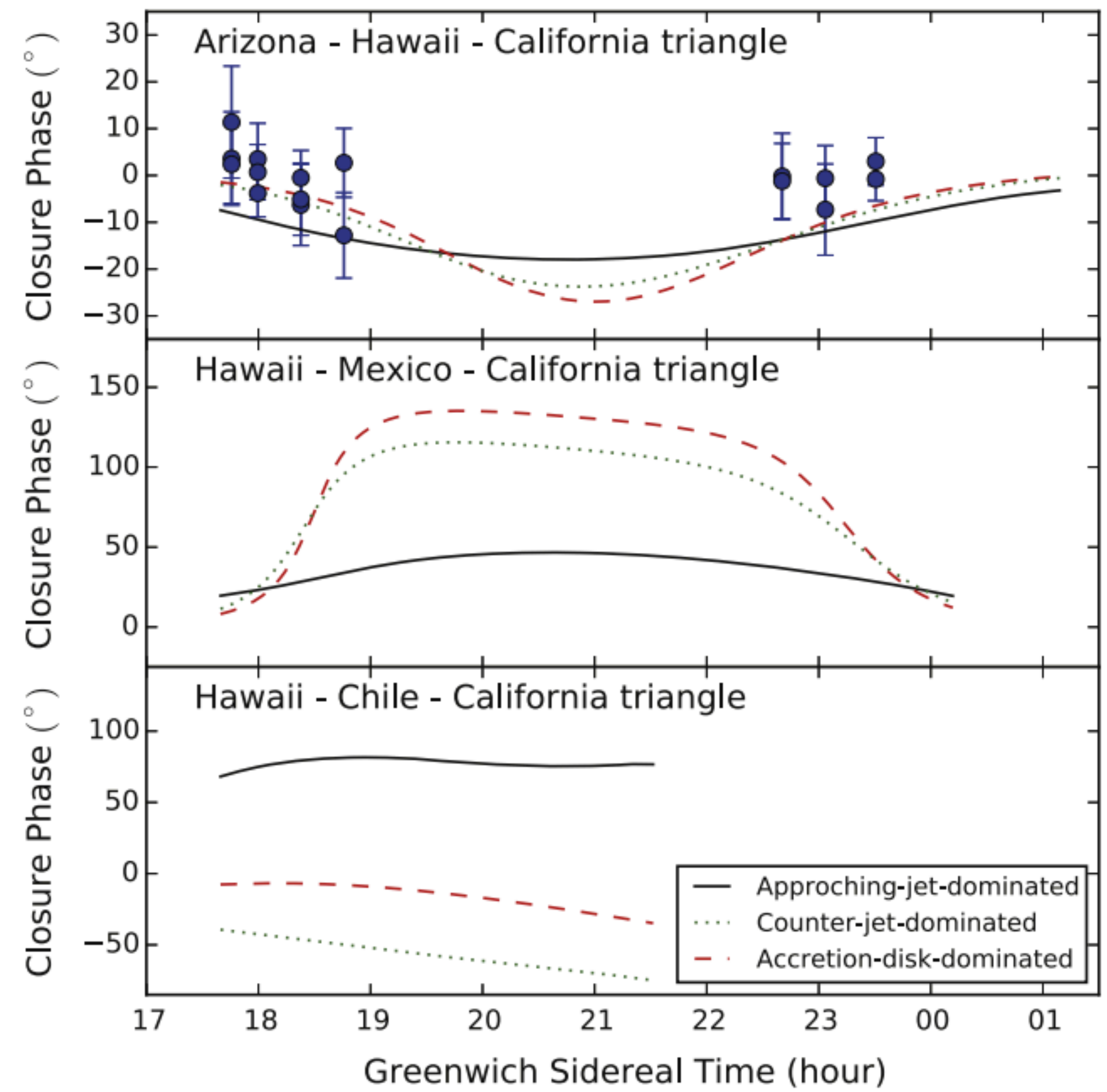
KAZUNORI AKIYAMA[1,2,22], RU-SEN LU[3,4], VINCENT L. FISH[3], SHEPERD S. DOELEMAN[3,5], AVERY E. BRODERICK[6,7], JASON DEXTER[8], KAZUHIRO HADA[2,9], MOTOKI KINO[10], HIROSHI NAGAI[2], MAREKI HONMA[2,11], MICHAEL D. JOHNSON[5], JUAN C. ALGABA[10,12], KEIICHI ASADA[12], CHRISTIAAN BRINKERINK[13], RAY BLUNDELL[5], GEOFFREY C. BOWER[14], ROGER CAPPALLO[3], GEOFFREY B. CREW[3], MATT DEXTER[15], SERGIO A. DZIB[4,16], ROBERT FREUND[17], PER FRIBERG[18], MARK GURWELL[5], PAUL T. P. HO[12], MAKOTO INOUE[12], THOMAS P. KRICHBAUM[4], LAURENT LOINARD[16], DAVID MACMAHON[15], DANIEL P. MARRONE[17], JAMES M. MORAN[5], MASANORI NAKAMURA[12], NEIL M. NAGAR[19], GISELA ORTIZ-LEON[16], RICHARD PLAMBECK[15], NICOLAS PRADEL[12], RURIK A. PRIMIANI[5], ALAN E. E. ROGERS[3], ALAN L. ROY[4], JASON SOOHOO[3], JONATHAN-LEÓN TAVARES[20], REMO P. J. TILANUS[13,21], MICHAEL TITUS[3], JAN WAGNER[4,10], JONATHAN WEINTROUB[5], PAUL YAMAGUCHI[5], KEN H. YOUNG[5], ANTON ZENSUS[4], AND LUCY M. ZIURYS[17]

# Proto-EHT observations of M87* in 1.3 mm

A story based on Wielgus et al. + EHTC, ApJ 2020

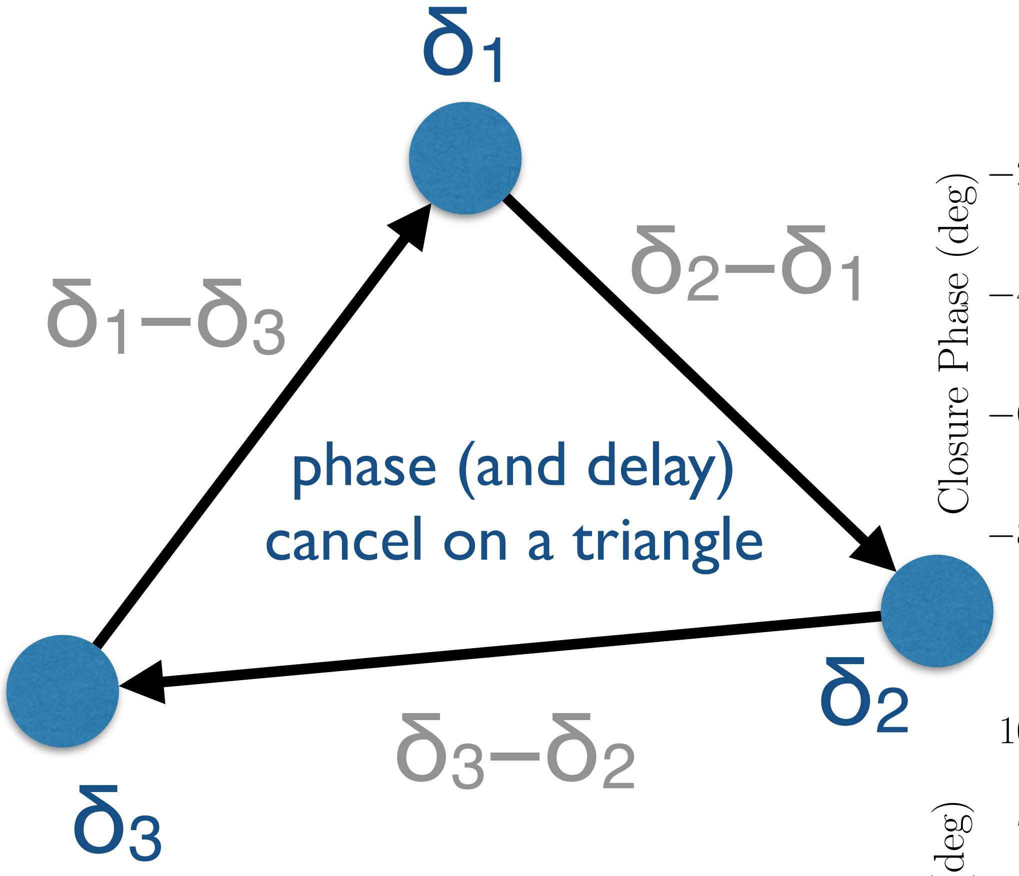



**detections in 2012**

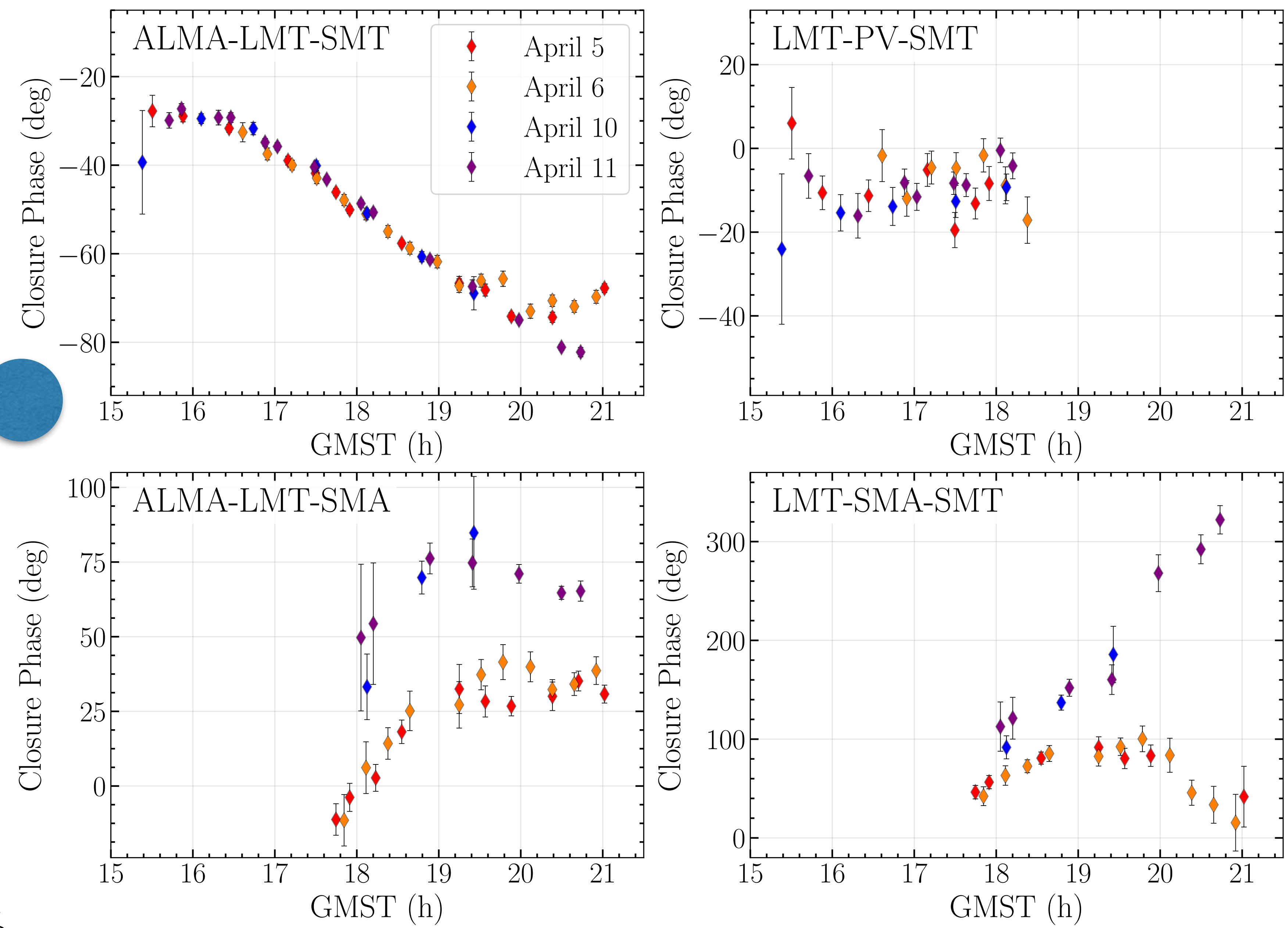



**first closure phases**

# Closure phases in 2017



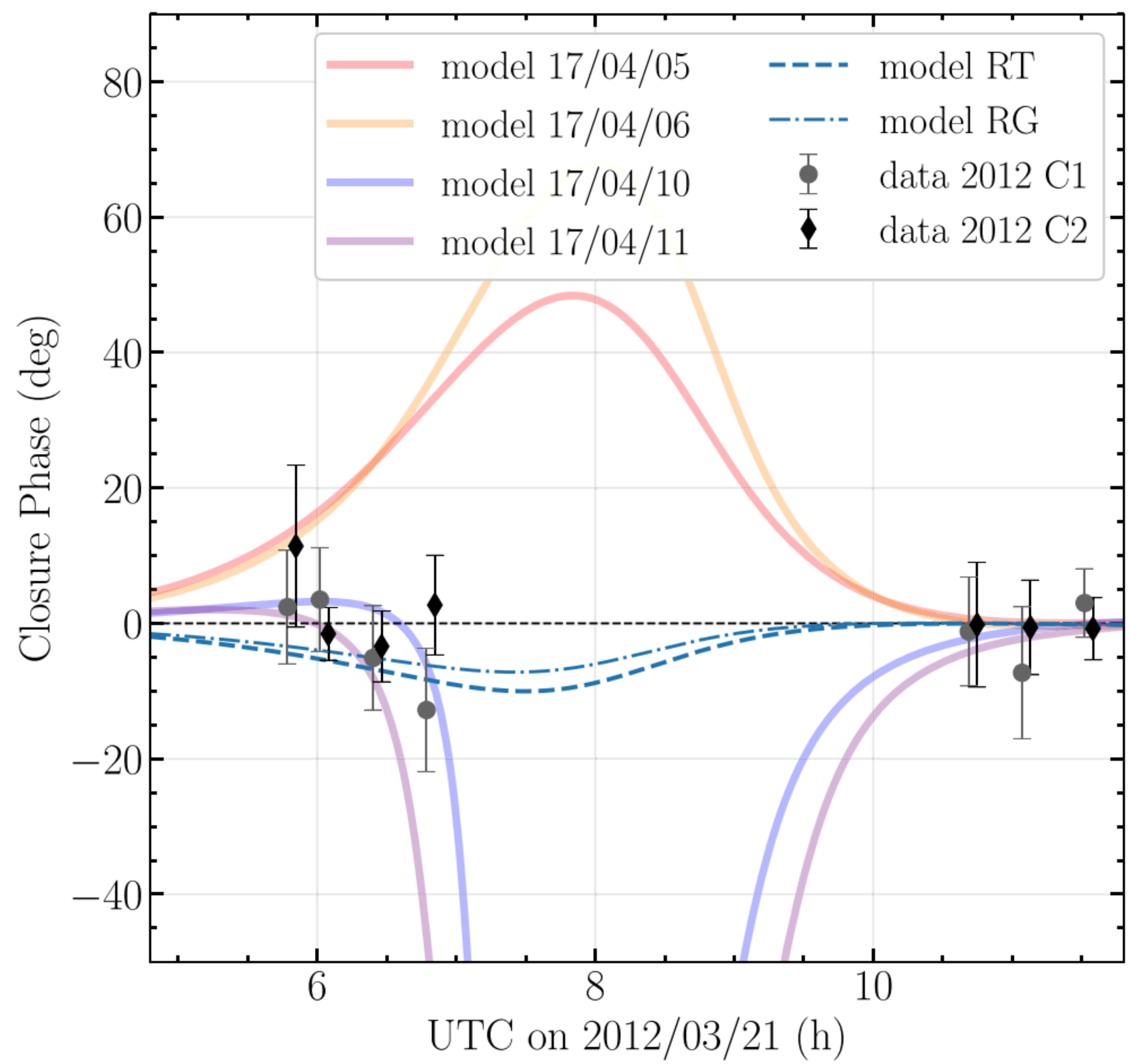

$$\phi'_{12} = \phi_{12} + \delta_2 - \delta_1$$
$$\phi'_{23} = \phi_{23} + \delta_3 - \delta_2$$
$$\phi'_{31} = \phi_{31} + \delta_1 - \delta_3$$
$$\phi'_{12} + \phi'_{23} + \phi'_{31} = \phi_{12} + \phi_{23} + \phi_{31}$$



# Synthetic 2017 closure phases on a 2012 triangle

A story based on Wielgus et al. + EHTC, ApJ 2020

**Probably we were quite unlucky in 2012…**



# Proto-EHT observations of M87* in 1.3 mm

A story based on Wielgus et al. + EHTC, ApJ 2020

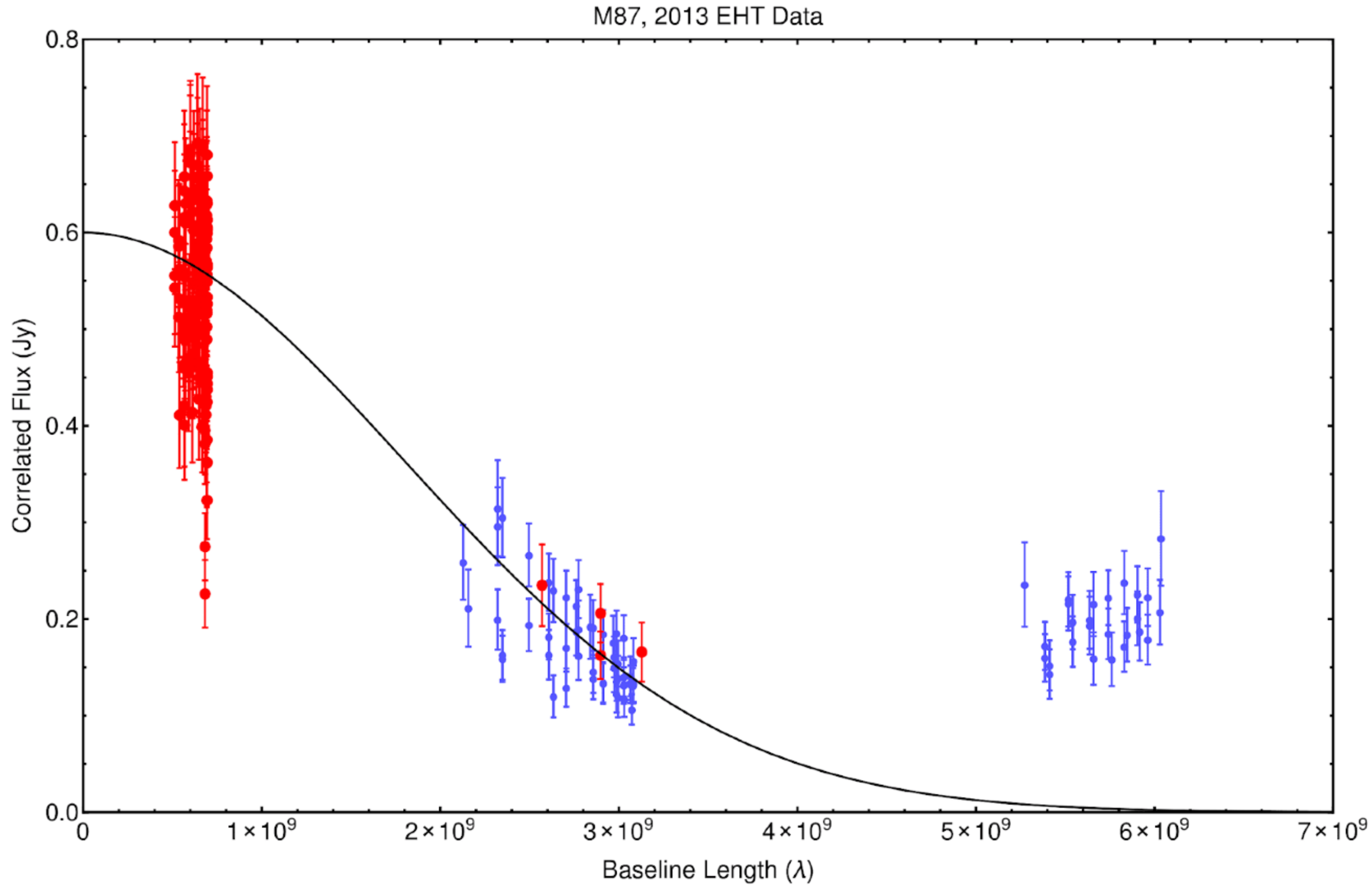

**2009:** CARMA + SMT + JCMT
*Doeleman et al 2012* - compact core of M87

**2011:** CARMA + SMT + JCMT/SMA/CSO
*Data calibrated, not published*

**2012:** CARMA + SMT + SMA
*Akiyama et al 2015* - first closure phases

**2013:** CARMA + SMT + JCMT/SMA + APEX
*Data calibrated, not published*

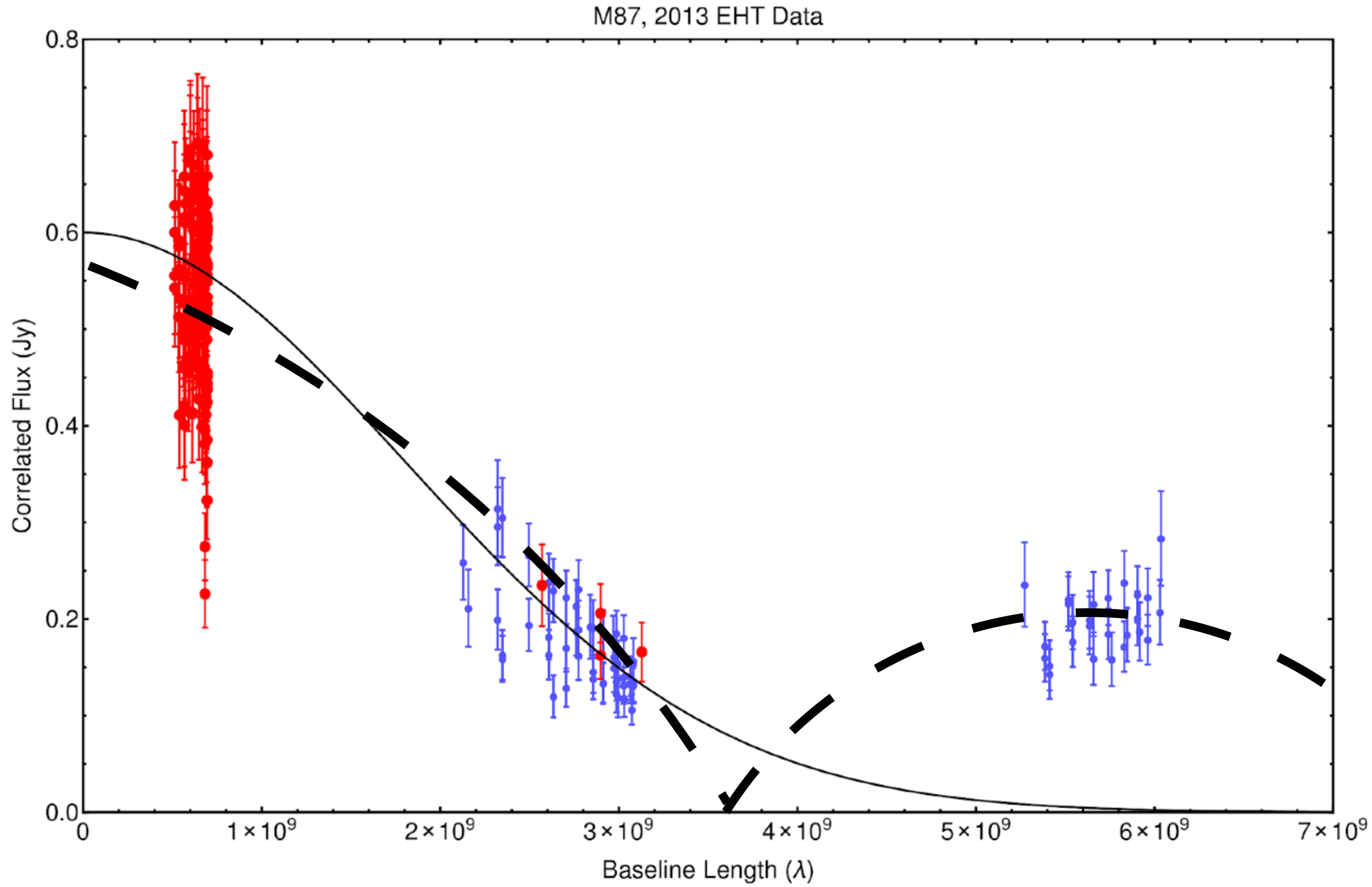
# Proto-EHT observations of M87* in 1.3 mm




[...] we can use the nearest network solution for 3C273 or 3C279 for each scan to approximately calibrate the data. Here is an example of the resulting calibration. Red points denote baselines to the SMT, blue are all other baselines. The black line is a Gaussian with FWHM of 43 microarcseconds and an integrated flux density of 0.6 Jy. The size of this Gaussian is very close to what Doeleman (2012) and Akiyama (2015) report, although the integrated flux is smaller (they each had ~1 Jy).
**The APEX detections (>5 G\lambda) clearly require a more complicated model.**

***Michael D. Johnson, 2015***

# Proto-EHT observations of M87* in 1.3 mm

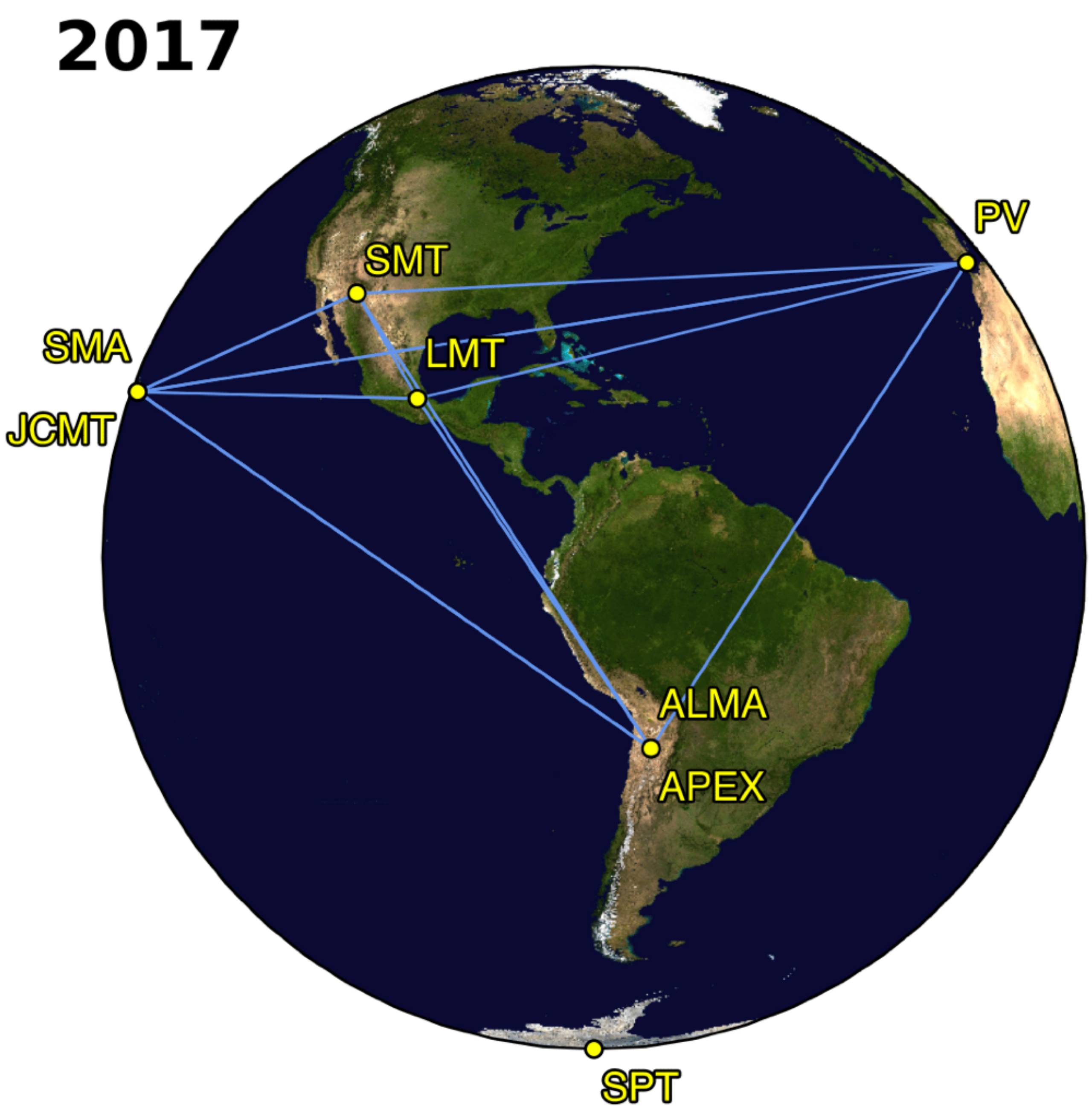



[...] we can use the nearest network solution for 3C273 or 3C279 for each scan to approximately calibrate the data. Here is an example of the resulting calibration. Red points denote baselines to the SMT, blue are all other baselines. The black line is a Gaussian with FWHM of 43 microarcseconds and an integrated flux density of 0.6 Jy. The size of this Gaussian is very close to what Doeleman (2012) and Akiyama (2015) report, although the integrated flux is smaller (they each had ~1 Jy).
**The APEX detections (>5 G\lambda) clearly require a more complicated model.**

***Michael D. Johnson, 2015***

# Proto-EHT observations of M87* in 1.3 mm

A story based on Wielgus et al. + EHTC, ApJ 2020




**2009:** CARMA + SMT + JCMT
*Doeleman et al 2012* - compact core of M87

**2011:** CARMA + SMT + JCMT/SMA/CSO
*Data calibrated, not published*

**2012:** CARMA + SMT + SMA
*Akiyama et al 2015* - first closure phases

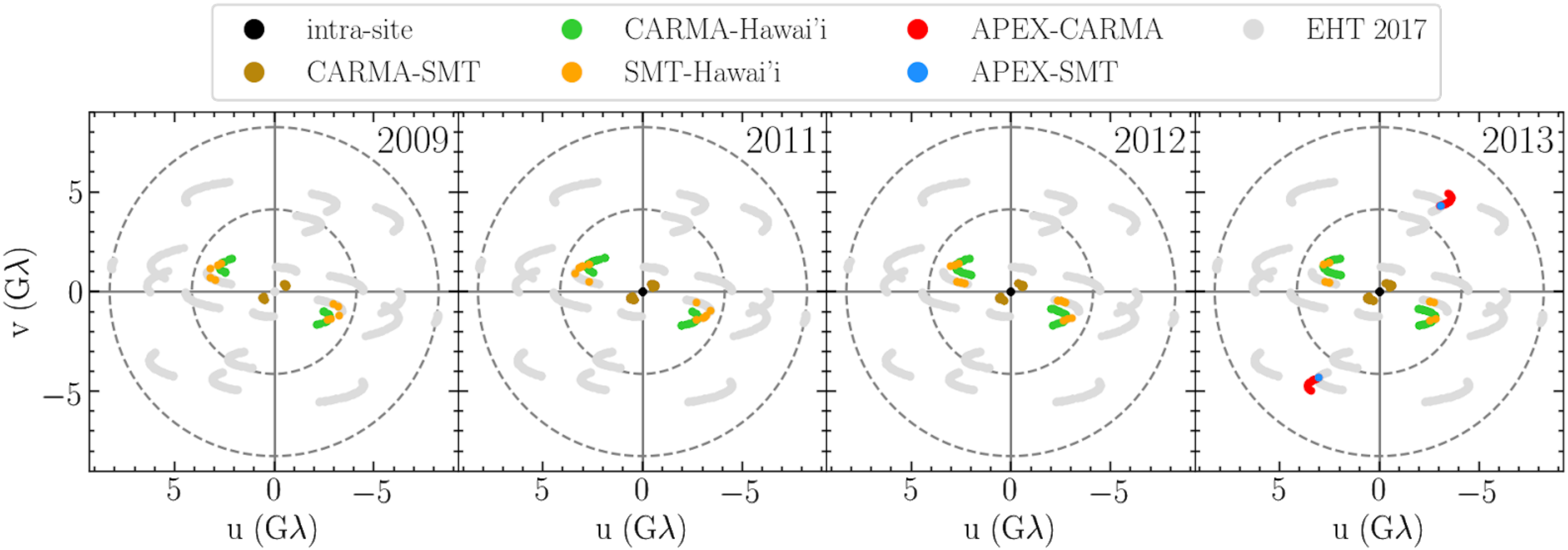
**2013:** CARMA + SMT + JCMT/SMA + APEX
*Data calibrated, not published*

**2015-2016:** *tests, uncalibrated data including non-zero closure phases on LMT-SMT-SMA*

***2017:*** *ALMA, APEX, SMA, JCMT, LMT, SMT, PV*
*EHT I-VI 2019* - first imaging of the M87* “shadow of a black hole”

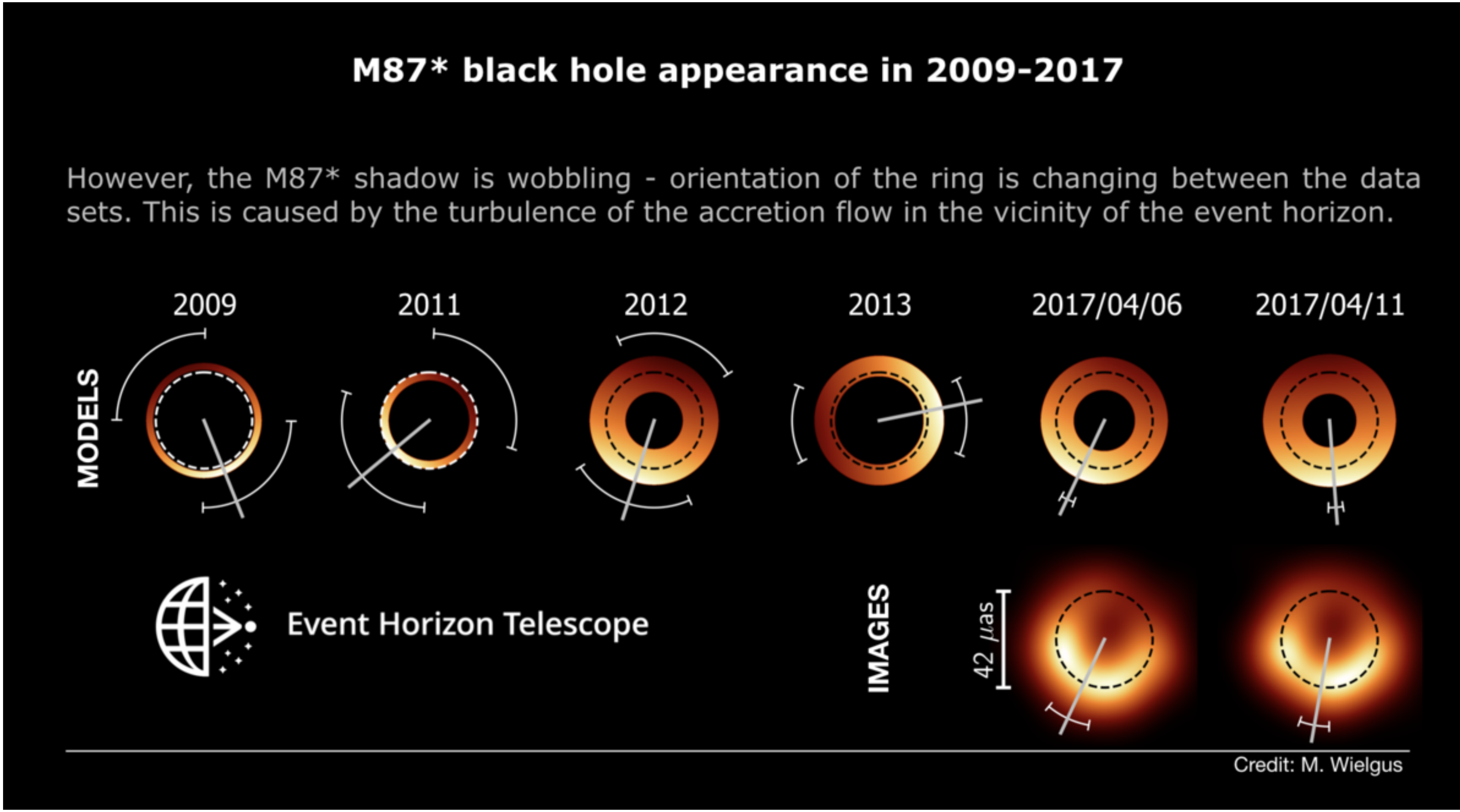
# Archival detections on M87*

A story based on Wielgus et al. + EHTC, ApJ 2020

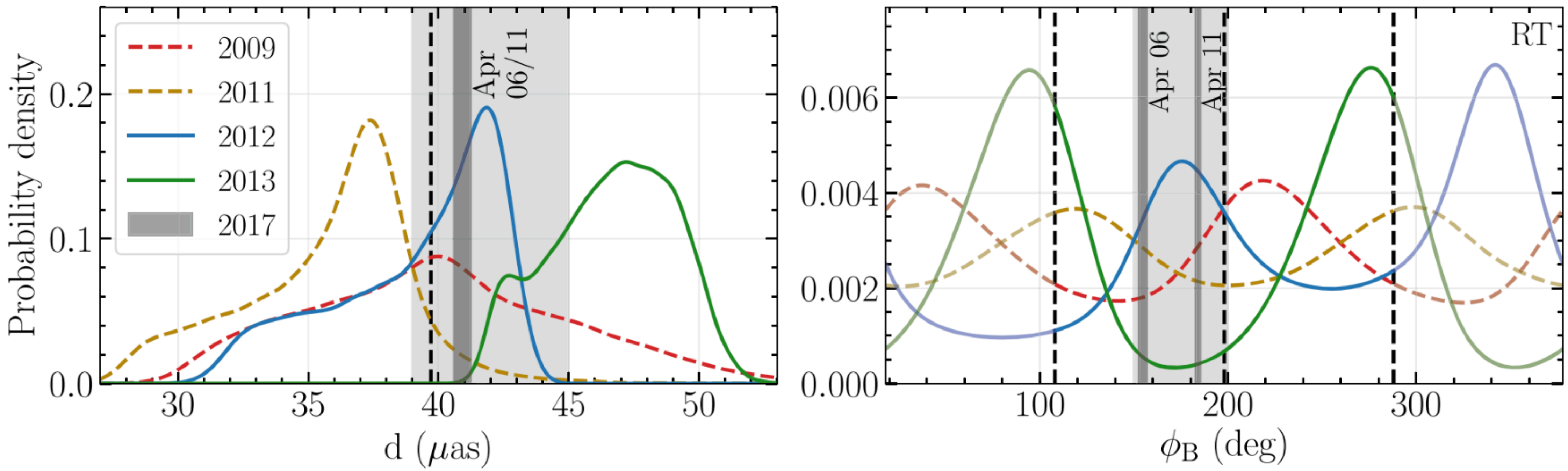



**Number of baselines grows with N²**

# Best-fit models of M87* in 2009-2017



# Diameter and orientation posteriors (MCMC)




| | $d$ (μas) | | $\phi_B$ (deg) | $f_w$ |
|---|---|---|---|---|
| Estimator | median | ML | ML | at most |
| Confidence | 68% | 95% | 68% | 95% |
| 2009 | $39.8^{+5.5}_{-5.2}$ | $47.3^{+3.1}_{-16.0}$ | $202^{+68}_{-23}$ | 0.93 |
| 2011 | $36.5^{+2.0}_{-4.3}$ | $38.6^{+2.8}_{-9.9}$ | (130) | 0.91 |
| 2012[a] | $40.1^{+2.1}_{-4.8}$ | $40.6^{+2.5}_{-8.3}$ | $342^{+42}_{-40}$ | 0.92 |
| 2013 | $46.8^{+2.3}_{-2.9}$ | $47.6^{+3.0}_{-5.5}$ | $281^{+17}_{-34}$ | 0.28 |
| 2017[b] | $41.1^{+0.1}_{-0.1}$ | $41.1^{+0.2}_{-0.2}$ | $155^{+1}_{-1}$ | 0.37 |
| 2017[c] | $40.7^{+0.1}_{-0.1}$ | $40.7^{+0.1}_{-0.1}$ | $184^{+1}_{-1}$ | 0.44 |

[a] secondary mode present at $\phi_B - 180°$ (see the text), [b] April 6th 2017, [c] April 11th 2017

# Global VLBI improvements since 2010 and 2020+

- ALMA joining as an anchor station,
- more sites / better coverage / more sanity checks,
- higher bandwidth,
- dual polarization,
- individual improvements at stations,
- algorithmic developments,
- enabling shorter wavelengths,
- ngEHT (New Generation EHT),
- space VLBI

# The power of ALMA

- incredible site: dry, cold, high altitude
- 66 antennas, allowing for the array reconfiguration
- cutting edge hardware

**ALMA**

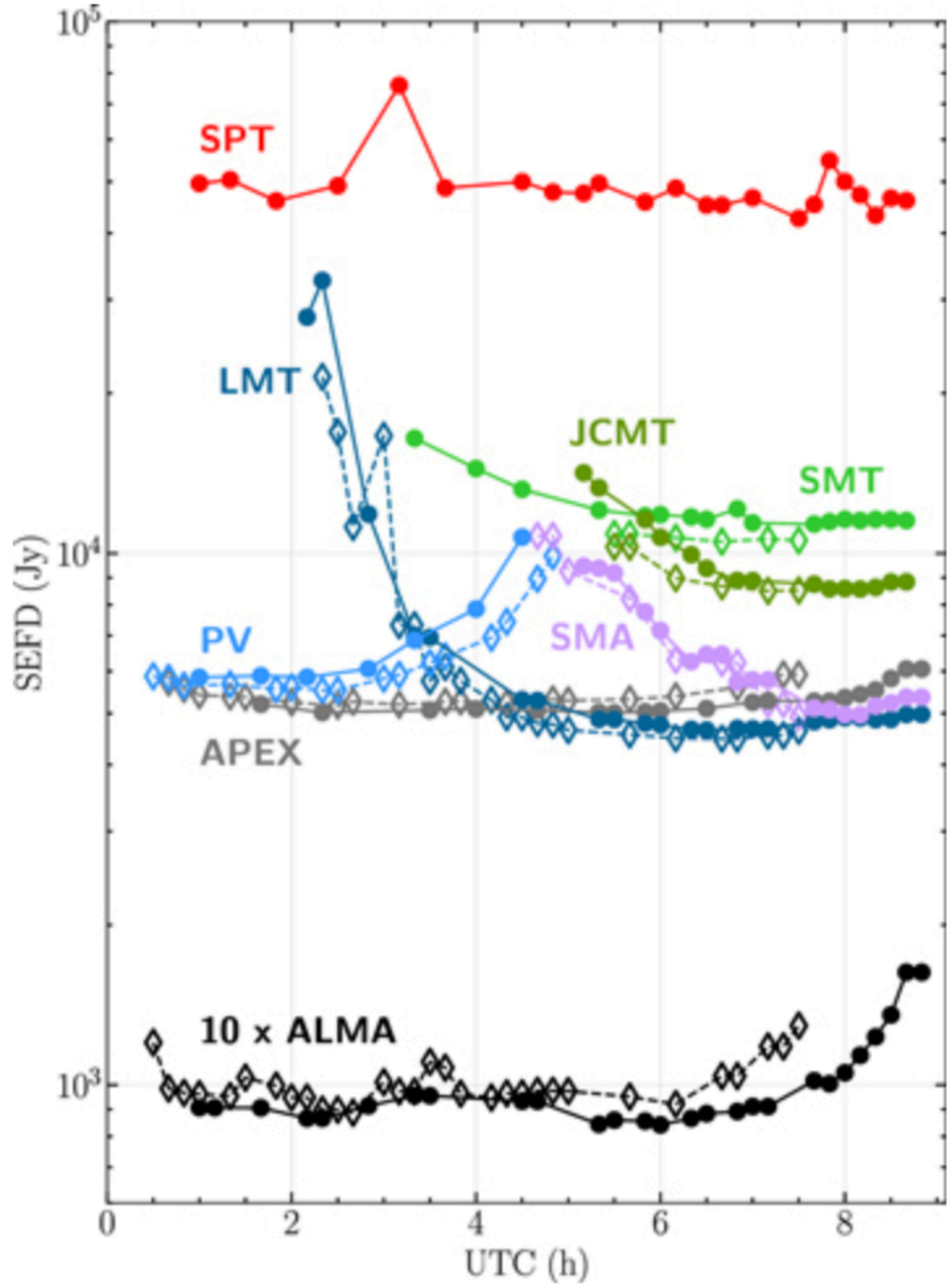
# The power of ALMA

- **incredible site: dry, cold, high altitude**
- **66 antennas, allowing for the array reconfiguration**
- **cutting edge hardware**

**ALMA**

**phased ALMA**

# The power of ALMA

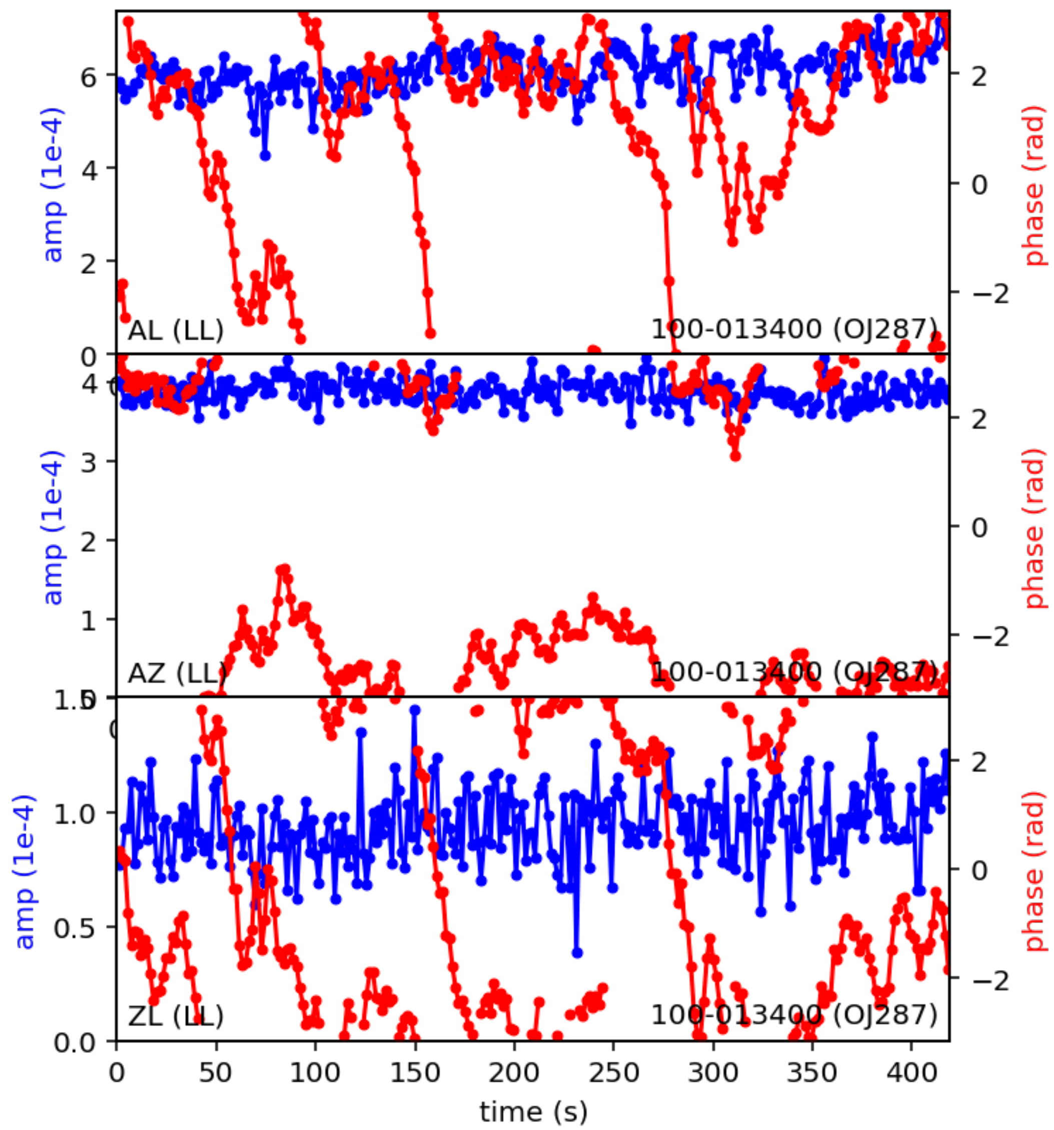


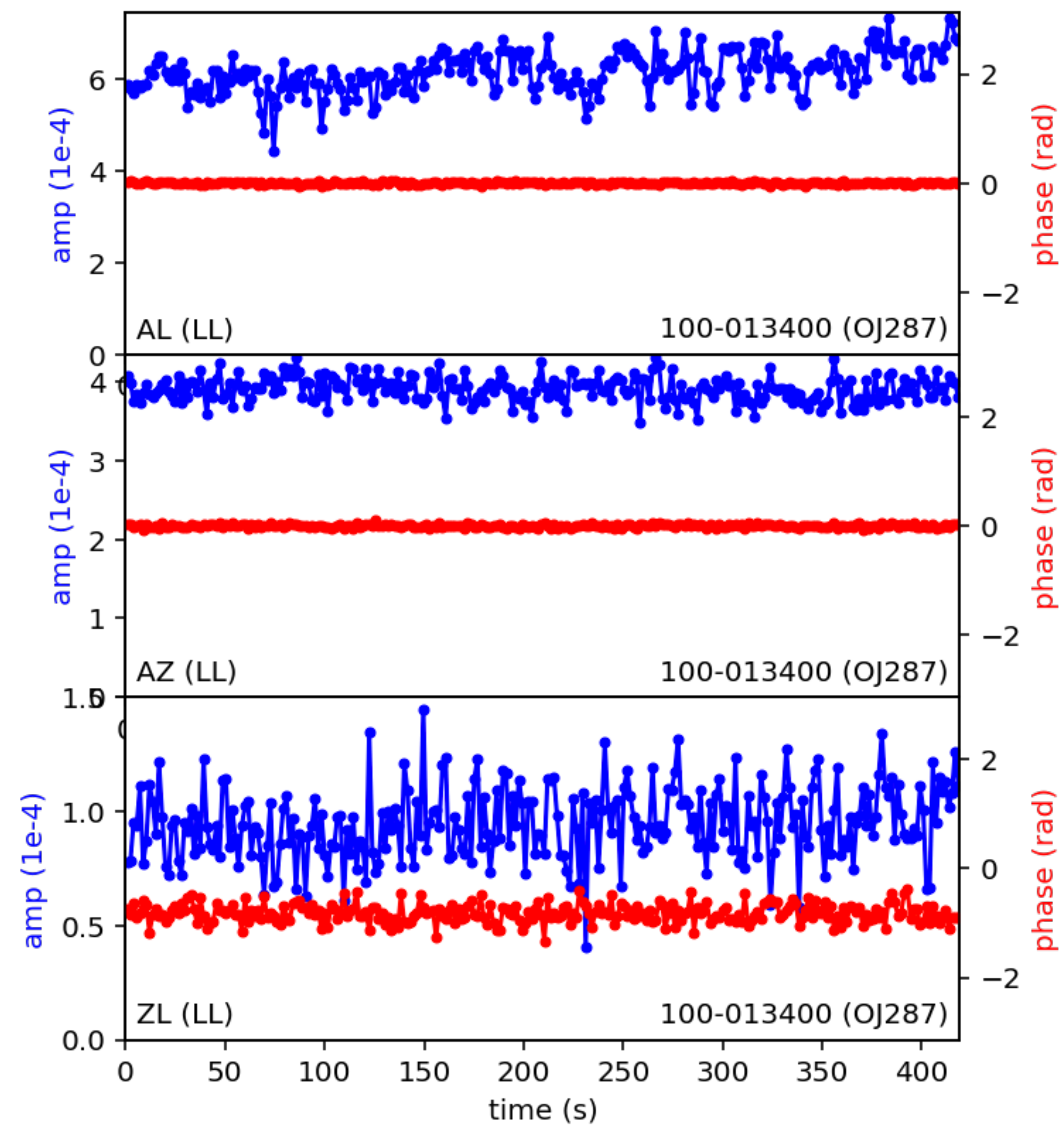

**EHTC+ 2019 ApJL 875 L3**

**phased ALMA**

# The power of ALMA

***before*** ***after***




***can only average for ~few seconds*** ***can average for entire scan***

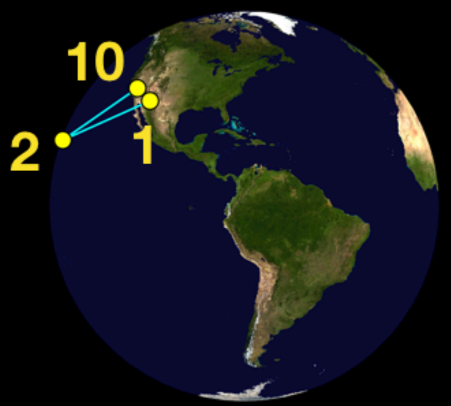
Event Horizon Telescope

**EHTC+ 2019 ApJL 875 L3, Blackburn et al 2019, Janssen et al 2019**

Credit: M. Wielgus, D. Pesce

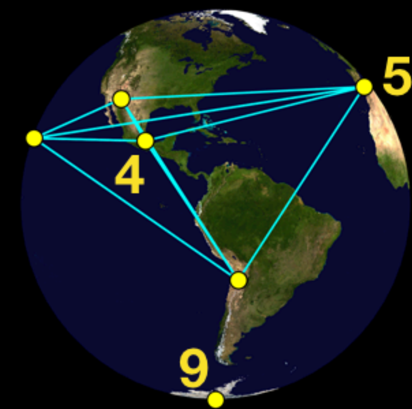
# MORE SITES

Event Horizon Telescope

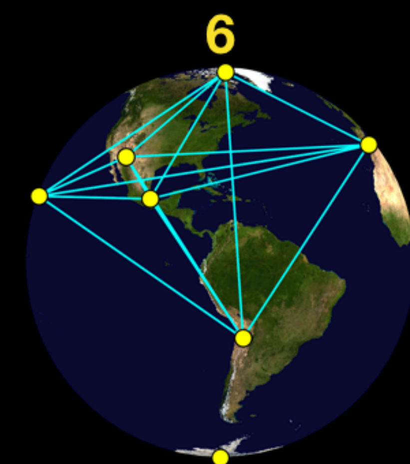



2009-2012


2013




2017




2018


2021

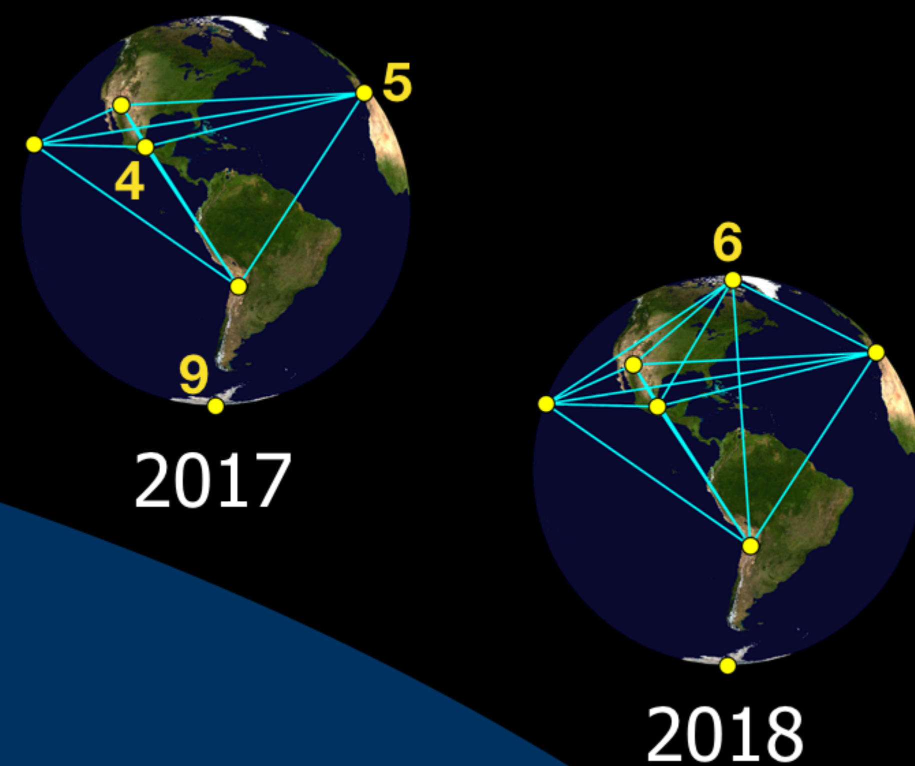
## The EHT array observing M87*

1. **Mt Graham, Arizona, USA**
   SMT: Submillimeter Telescope (since 2009)
2. **Maunakea, Hawai'i, USA**
   JCMT: James Clerk Maxwell Telescope (since 2009)
   SMA: Submillimeter Array (since 2011)
   CSO: Caltech Submillimeter Observatory (2011)
3. **Atacama, Chile**
   APEX: Atacama Pathfinder Experiment (since 2013)
   ALMA: Atacama Large Millimeter/submillimeter Array (since 2017)
4. **Sierra Negra, Mexico**
   LMT: Large Millimeter Telescope Alfonso Serrano (since 2017)
5. **Pico Veleta, Spain**
   IRAM 30m: IRAM 30-meter telescope (since 2017)
6. **Thule, Greenland**
   GLT: Greenland Telescope (since 2018)
7. **Plateau de Bure, France**
   NOEMA: NOrthern Extended Millimeter Array (since 2021)
8. **Kitt Peak, Arizona, USA**
   KP: ARO 12m Radio Telescope (since 2021)
9. **South Pole**
   SPT: South Pole Telescope (since 2017, not directly observing M87*)
10. **Cedar Flat, California, USA**
    CARMA: Combined Array for Research in Millimeter-wave Astronomy (2009-2013)

Credit: M. Wielgus, D. Pesce

**BANDWIDTH**

Event Horizon Telescope



## The EHT array observing M87*

1. **Mt Graham, Arizona, USA**
   SMT: Submillimeter Telescope (since 2009)
2. **Maunakea, Hawai'i, USA**
   JCMT: James Clerk Maxwell Telescope (since 2009)
   SMA: Submillimeter Array (since 2011)
   CSO: Caltech Submillimeter Observatory (2011)
3. **Atacama, Chile**
   APEX: Atacama Pathfinder Experiment (since 2013)
   ALMA: Atacama Large Millimeter/submillimeter Array (since 2017)
4. **Sierra Negra, Mexico**
   LMT: Large Millimeter Telescope Alfonso Serrano (since 2017)
5. **Pico Veleta, Spain**
   IRAM 30m: IRAM 30-meter telescope (since 2017)
6. **Thule, Greenland**
   GLT: Greenland Telescope (since 2018)
7. **Plateau de Bure, France**
   NOEMA: NOrthern Extended Millimeter Array (since 2021)
8. **Kitt Peak, Arizona, USA**
   KP: ARO 12m Radio Telescope (since 2021)
9. **South Pole**
   SPT: South Pole Telescope (since 2017, not directly observing M87*)
10. **Cedar Flat, California, USA**
    CARMA: Combined Array for Research in Millimeter-wave Astronomy (2009-2013)

Credit: M. Wielgus, D. Pesce

**BANDWIDTH**

Event Horizon Telescope





## The EHT array observing M87*

1. **Mt Graham, Arizona, USA**
   SMT: Submillimeter Telescope (since 2009)
2. **Maunakea, Hawai'i, USA**
   JCMT: James Clerk Maxwell Telescope (since 2009)
   SMA: Submillimeter Array (since 2011)
   CSO: Caltech Submillimeter Observatory (2011)
3. **Atacama, Chile**
   APEX: Atacama Pathfinder Experiment (since 2013)
   ALMA: Atacama Large Millimeter/submillimeter Array (since 2017)
4. **Sierra Negra, Mexico**
   LMT: Large Millimeter Telescope Alfonso Serrano (since 2017)
5. **Pico Veleta, Spain**
   IRAM 30m: IRAM 30-meter telescope (since 2017)
6. **Thule, Greenland**
   GLT: Greenland Telescope (since 2018)
7. **Plateau de Bure, France**
   NOEMA: NOrthern Extended Millimeter Array (since 2021)
8. **Kitt Peak, Arizona, USA**
   KP: ARO 12m Radio Telescope (since 2021)
9. **South Pole**
   SPT: South Pole Telescope (since 2017, not directly observing M87*)
10. **Cedar Flat, California, USA**
    CARMA: Combined Array for Research in Millimeter-wave Astronomy (2009-2013)

Credit: M. Wielgus, D. Pesce

**BANDWIDTH**

Event Horizon Telescope

**2 x 480 MHz**


2009-2012


2013

**2 x 2 GHz**


2017

**4 x 2 GHz (212-216GHz, 226-230GHz)**


2018


2021

**all dual pol**

## The EHT array observing M87*

1. **Mt Graham, Arizona, USA**
   SMT: Submillimeter Telescope (since 2009)
2. **Maunakea, Hawai'i, USA**
   JCMT: James Clerk Maxwell Telescope (since 2009)
   SMA: Submillimeter Array (since 2011)
   CSO: Caltech Submillimeter Observatory (2011)
3. **Atacama, Chile**
   APEX: Atacama Pathfinder Experiment (since 2013)
   ALMA: Atacama Large Millimeter/submillimeter Array (since 2017)
4. **Sierra Negra, Mexico**
   LMT: Large Millimeter Telescope Alfonso Serrano (since 2017)
5. **Pico Veleta, Spain**
   IRAM 30m: IRAM 30-meter telescope (since 2017)
6. **Thule, Greenland**
   GLT: Greenland Telescope (since 2018)
7. **Plateau de Bure, France**
   NOEMA: NOrthern Extended Millimeter Array (since 2021)
8. **Kitt Peak, Arizona, USA**
   KP: ARO 12m Radio Telescope (since 2021)
9. **South Pole**
   SPT: South Pole Telescope (since 2017, not directly observing M87*)
10. **Cedar Flat, California, USA**
    CARMA: Combined Array for Research in Millimeter-wave Astronomy (2009-2013)

## Since 2018 EHT records:

4 bands x 2 GHz x 2 bits x 2 (Nyquist) x 2 polarizations

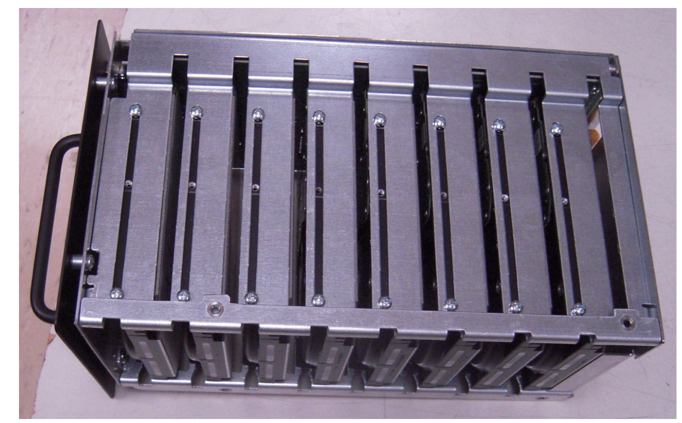
=

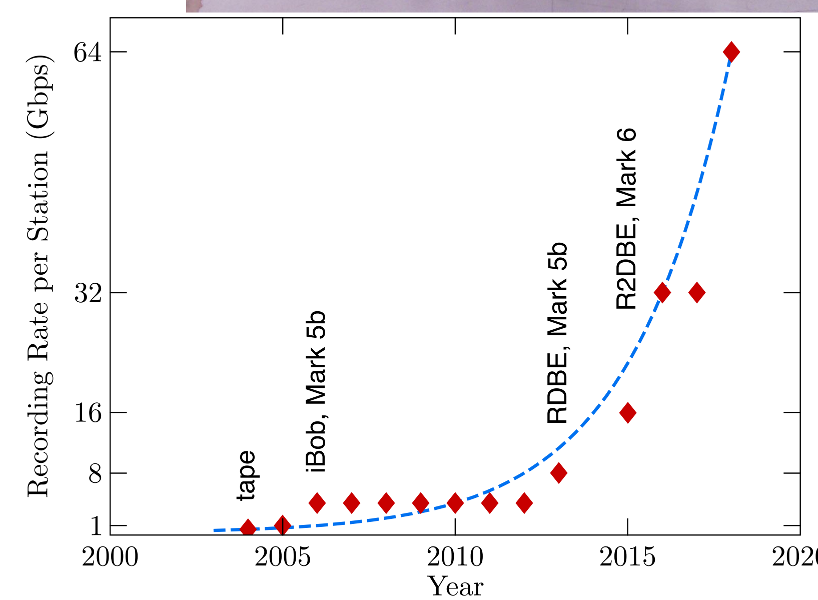
**64 Gbps** x number of telescopes

Digital backends

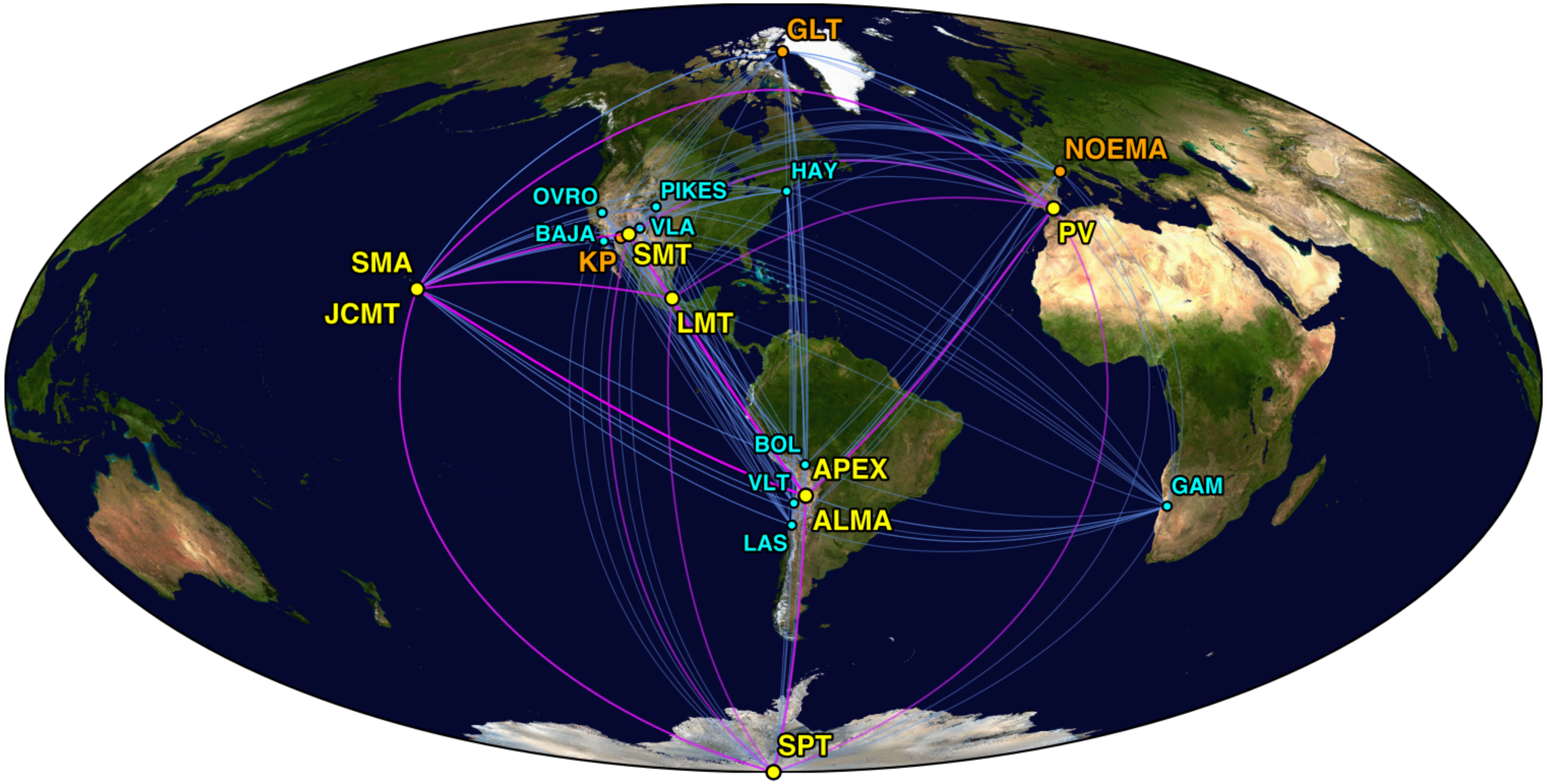
Down-converters

Recorders





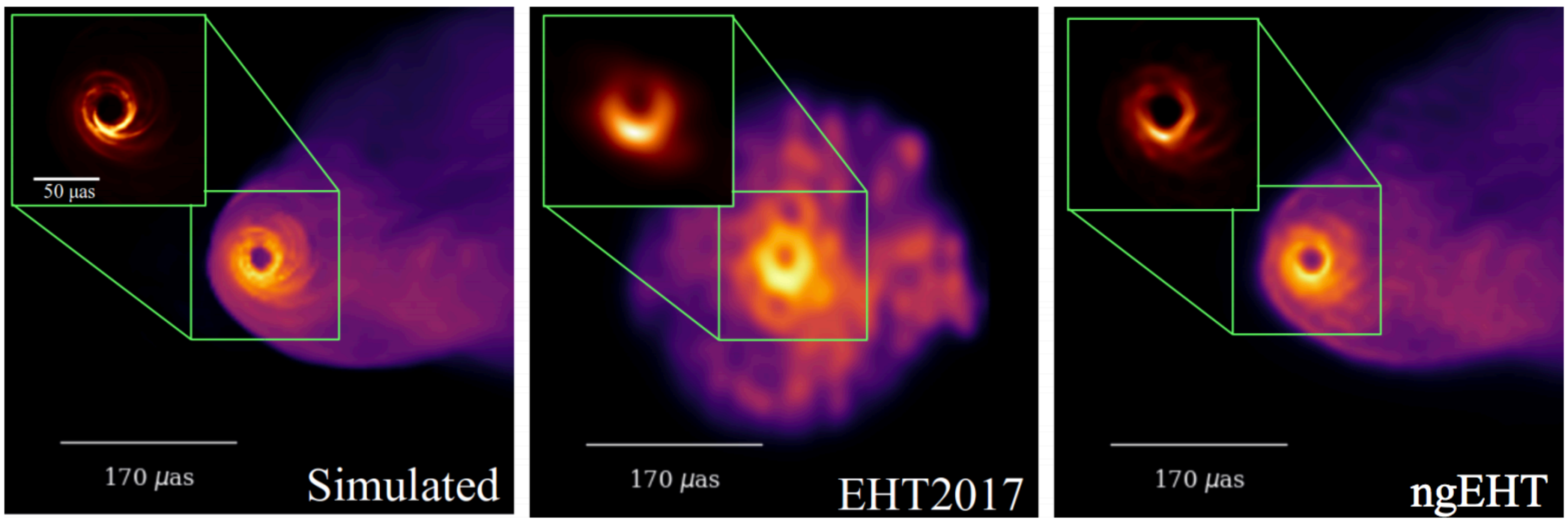
# ngEHT concept (2025+)




**Astro2020 Decadal Survey white papers on the future of the EHT:**
*Studying black holes on horizon scales with space-VLBI*, Johnson et al., arXiv:1909.01405,
*Extremely long baseline interferometry with Origins Space Telescope*, Pesce et al., arXiv:1909.01408,
*Studying Black Holes on Horizon Scales with VLBI Ground Arrays*, Blackburn, et al., arXiv:1909.01411,
*Black Hole Physics on Horizon Scales*, Doeleman et al., BAAS, 51, 537(2019)

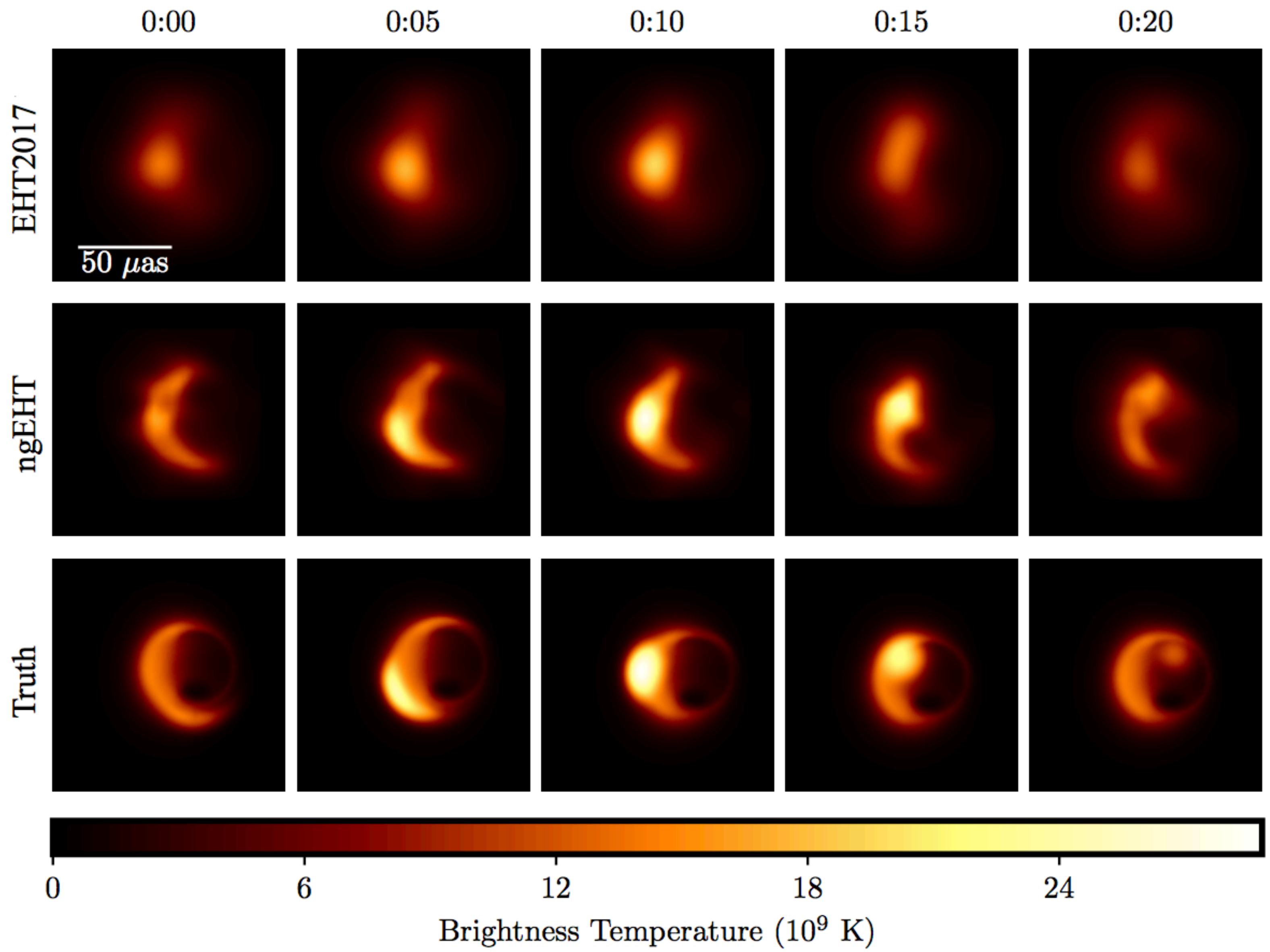
# Image fidelity and jet physics

- more detections: higher fidelity, improved dynamic range,
- more short (100-1000 km) baselines: larger field of view,
- resolution improvement, multifrequency reconstruction,
- ring / jet connection will be revealed,
- polarimetry will allow to study jet - magnetic field relationship




Credit: Andrew Chael

# Reconstruction of rapidly varying structures (Sgr A*)

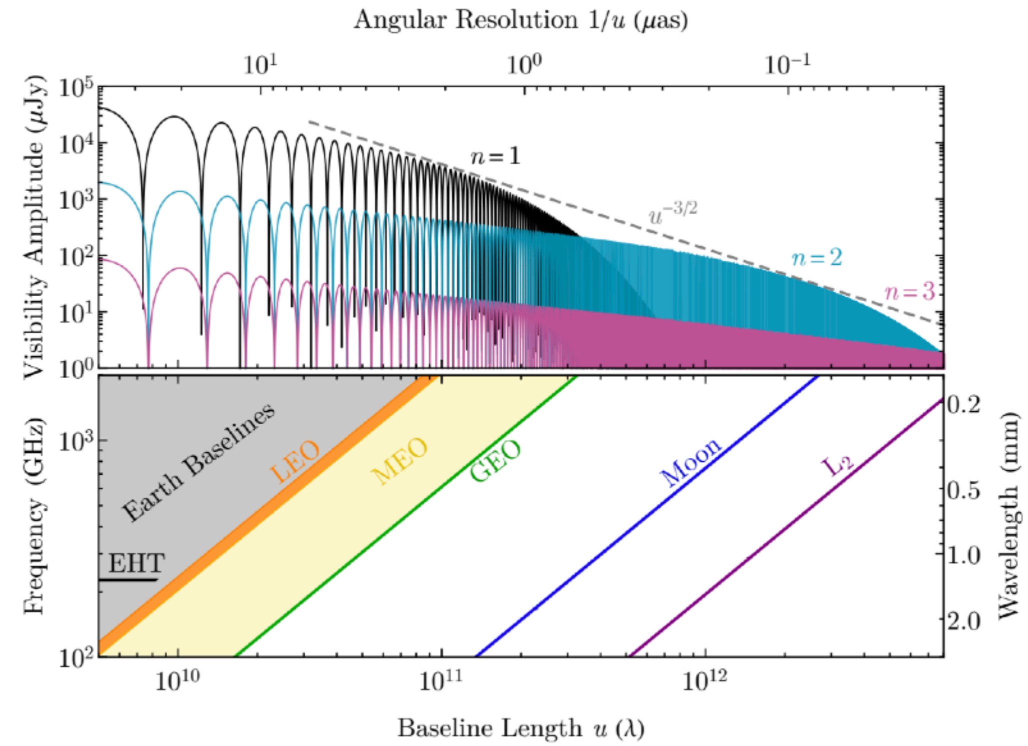


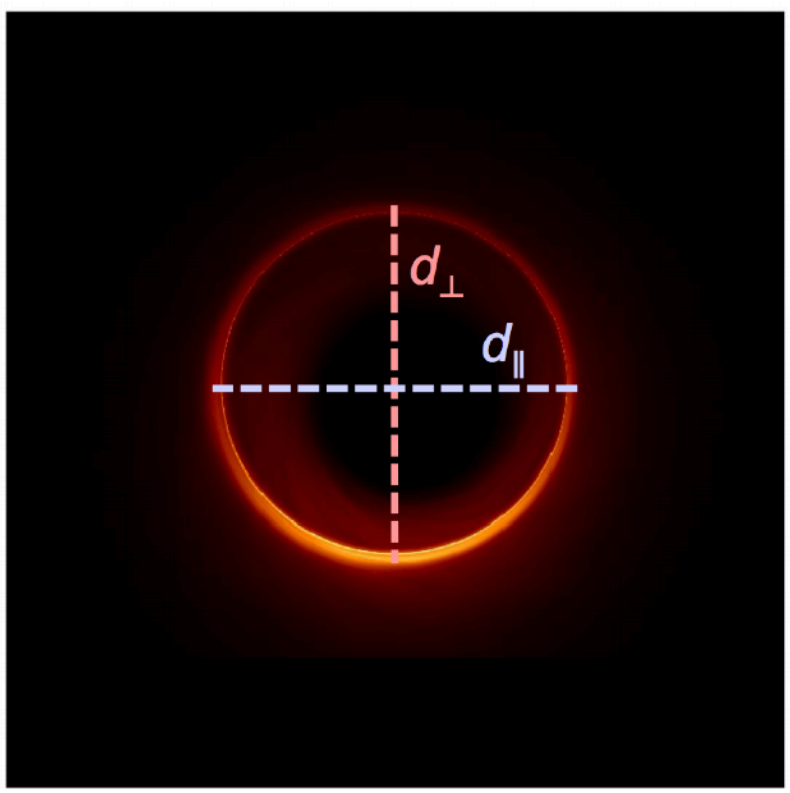
# Testing gravity

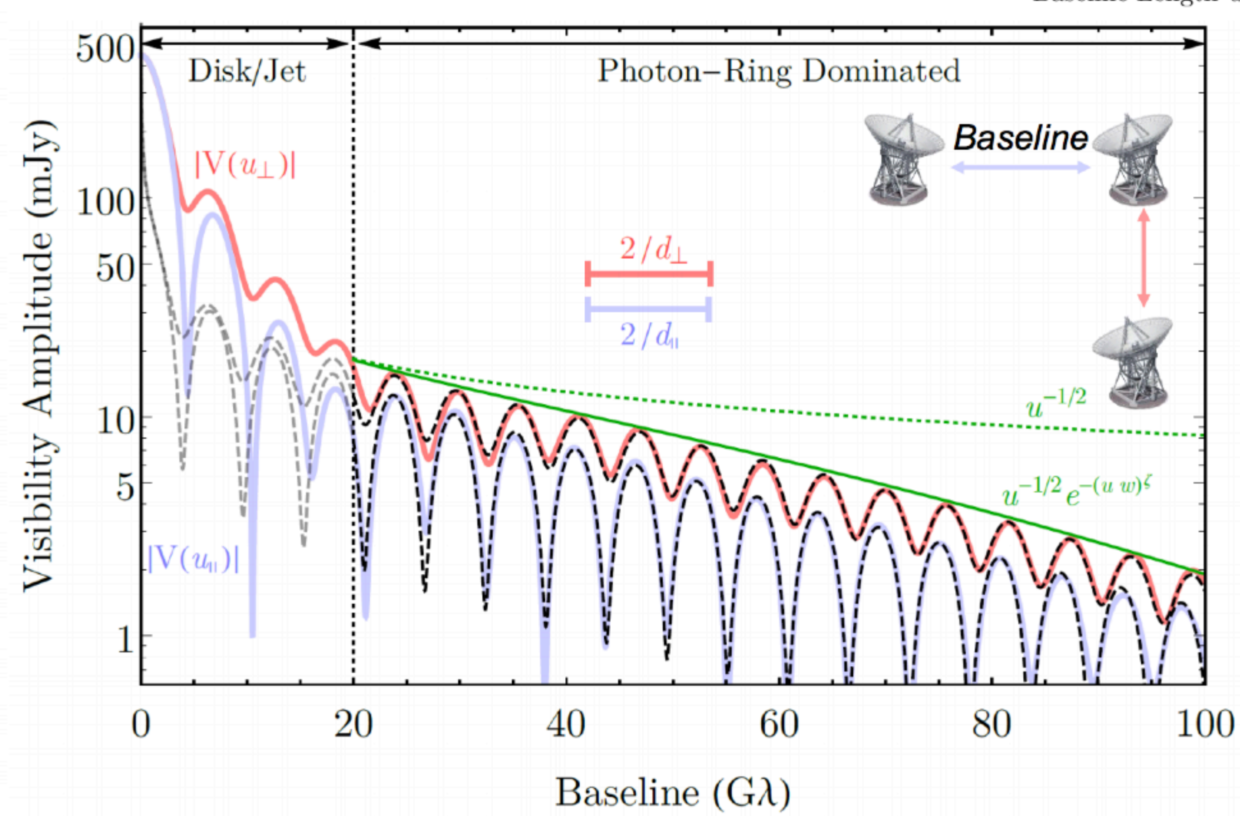
*Universal interferometric signatures of a black hole's photon ring*, Johnson, M.; Lupsasca, A.; Strominger, A.; Wong, G.; Hadar, S.; Kapec, D.; Narayan, R.; Chael, A.; Gammie, Ch.; Galison, P.; Palumbo, D.; Doeleman, S.; Blackburn, L.; **Wielgus, M.**; Pesce, D.; Farah, J.; Moran, J., Science Advances (2020)

Vincent, **Wielgus**, Abramowicz et al., A&A in press (2021)

Gralla & Lupsasca, PRD 2020

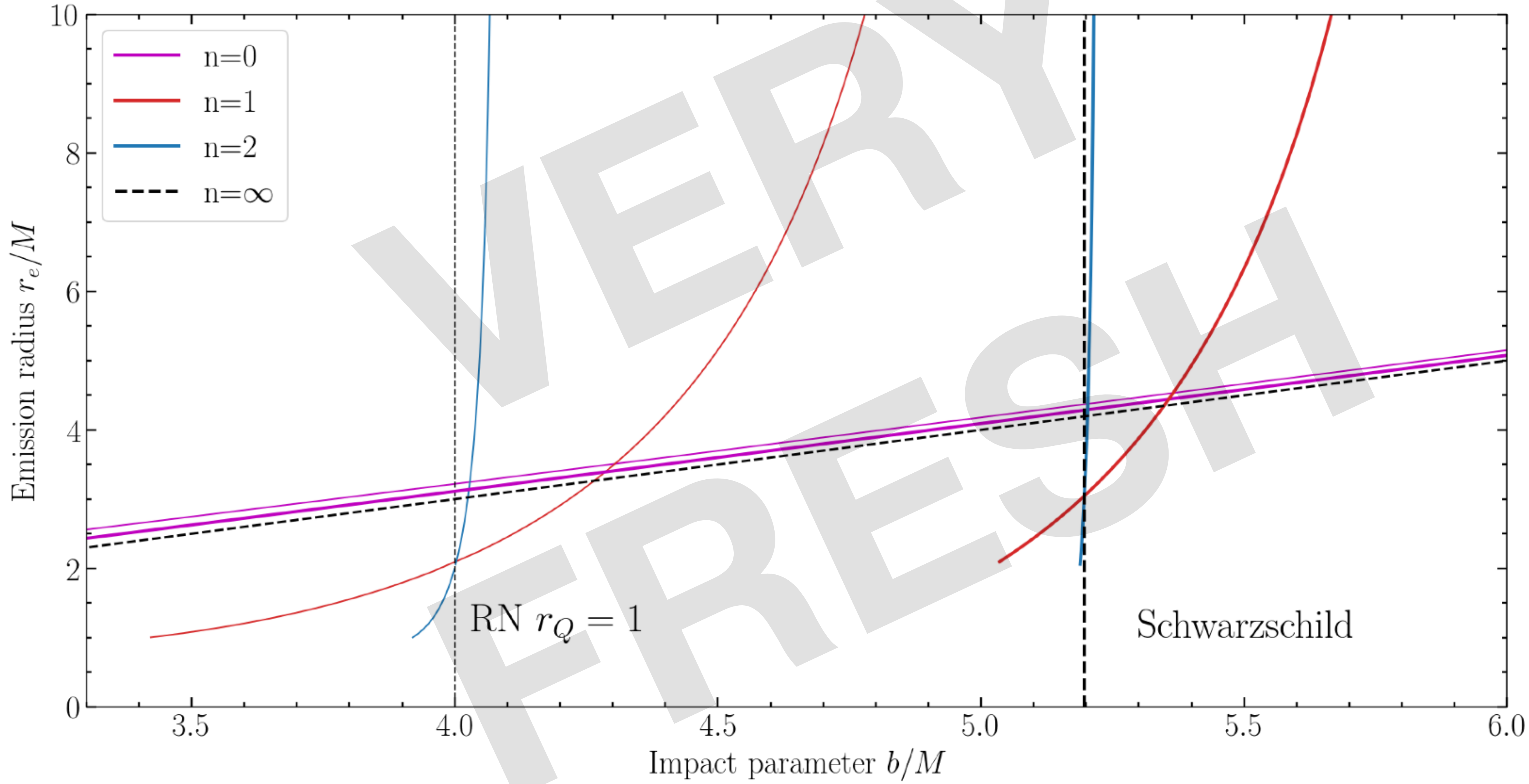



Credit: Michael Johnson

# Testing gravity

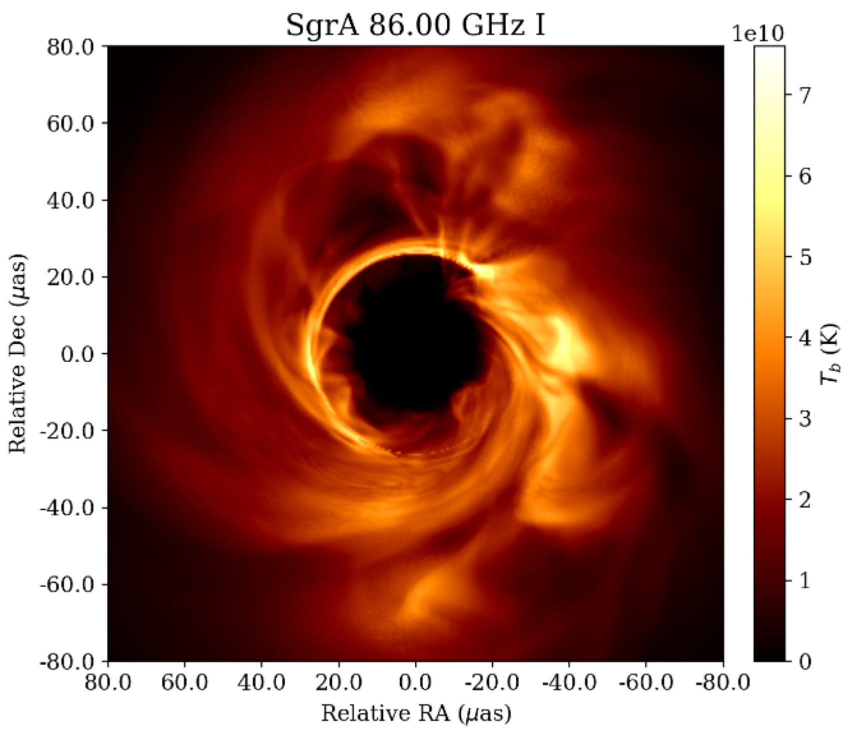



**Wielgus 2021, in prep**

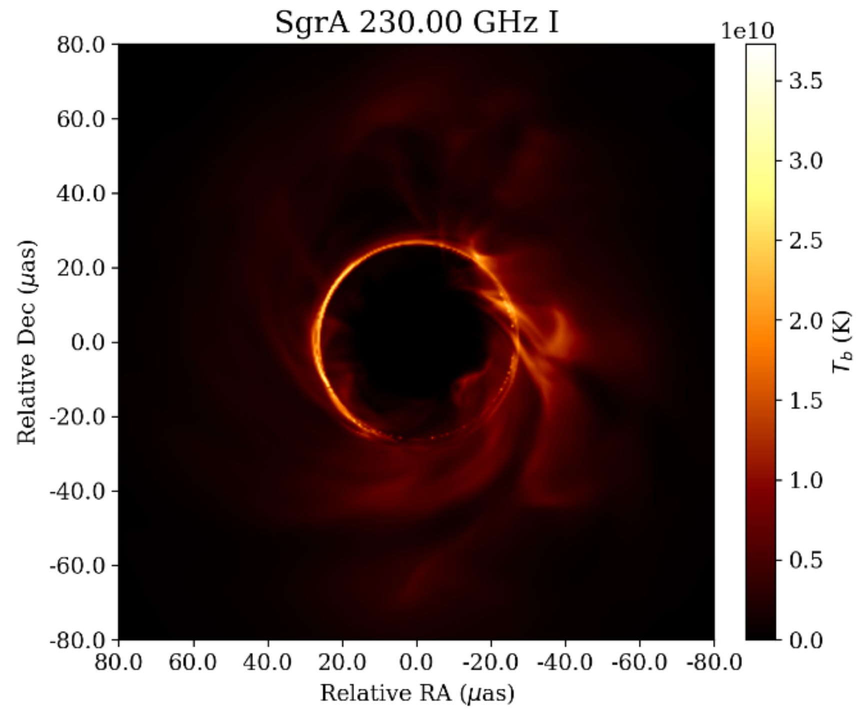
# Testing gravity and multifrequency imaging

- gravity is achromatic,
- a lot of interesting astrophysics is chromatic,
- probing resolved Faraday rotation

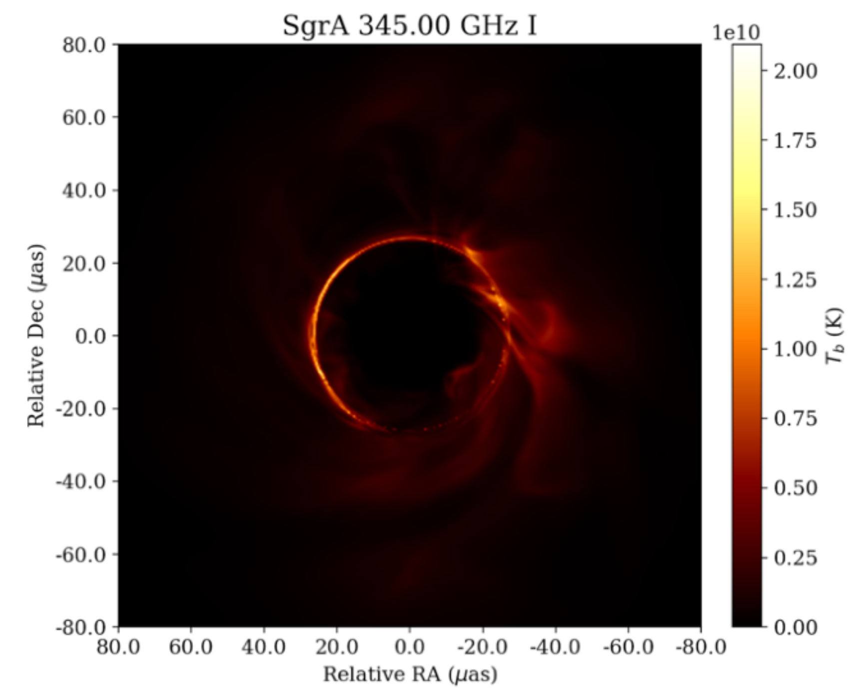
Credit: Zack Gelles




**86GHz (3.5mm)**
**First VLBI: ~1980**
**First VLBI image: 2000s (?)**

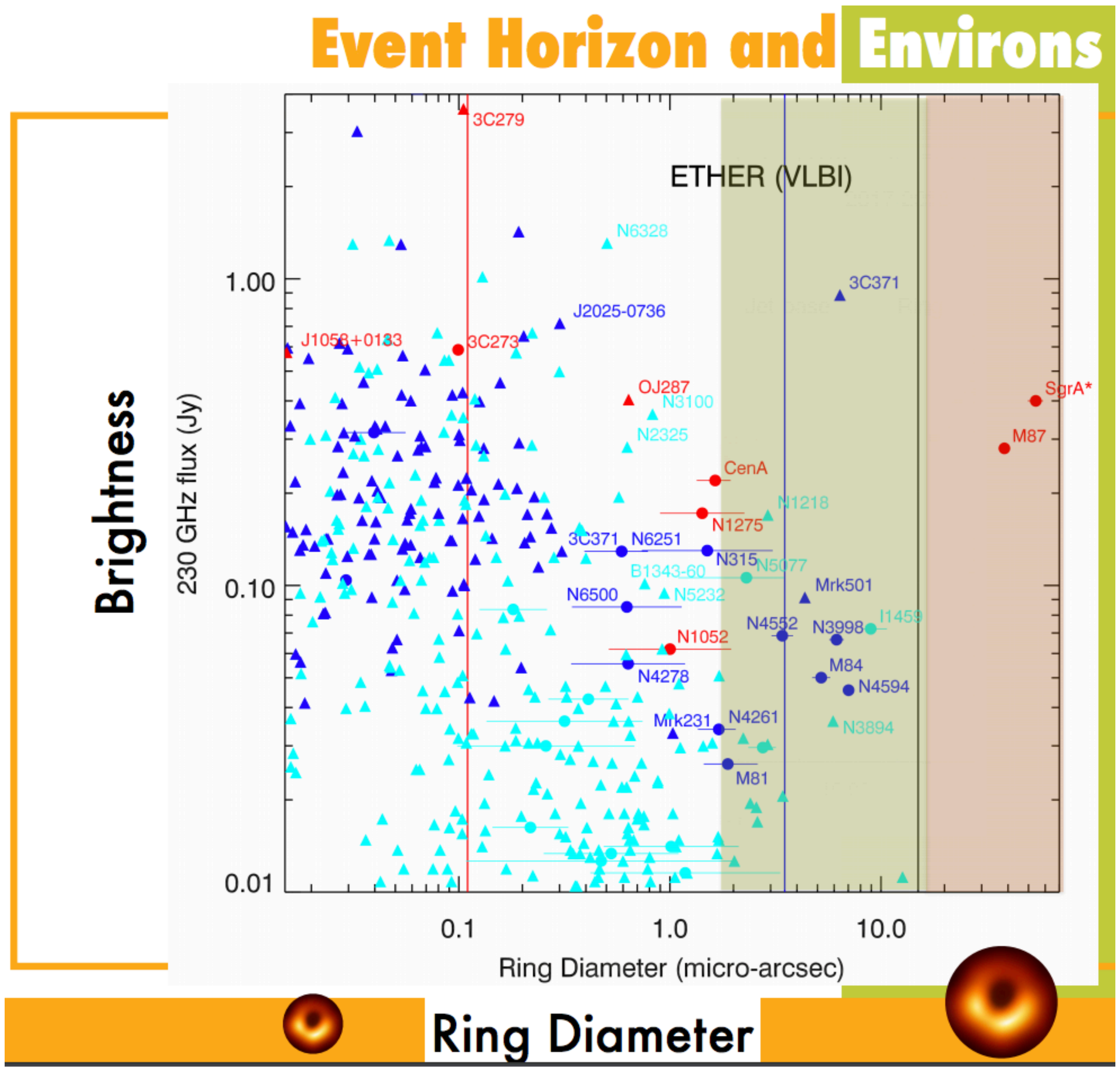



**230GHz (1.3mm)**
**First VLBI: 1989**
**First VLBI image: 2017**




**345GHz (0.86mm)**
**First VLBI: 2018**
**First VLBI image: < 2030**

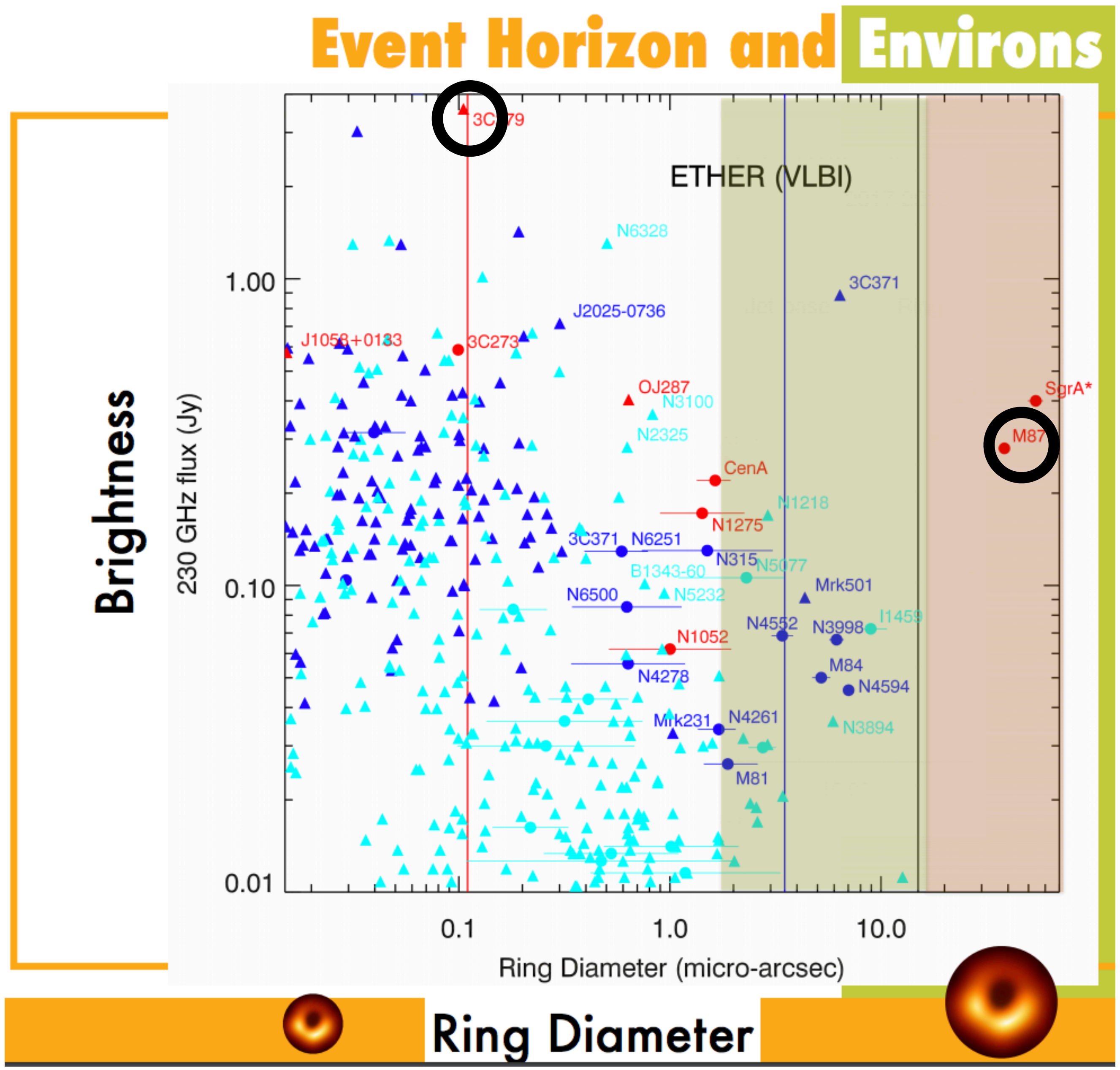
# More targets



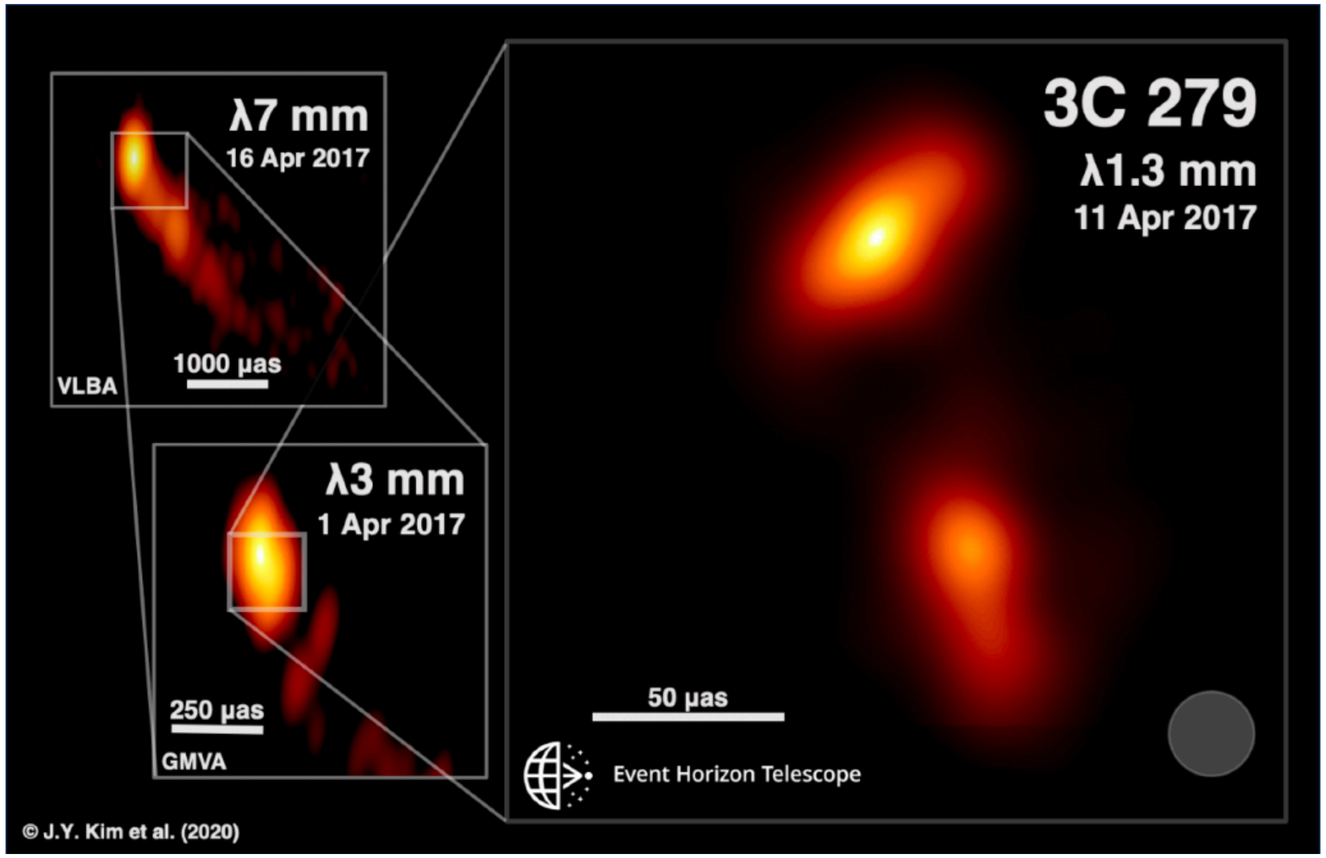

Credit: Neil Nagar

Event Horizon Telescope

# More targets

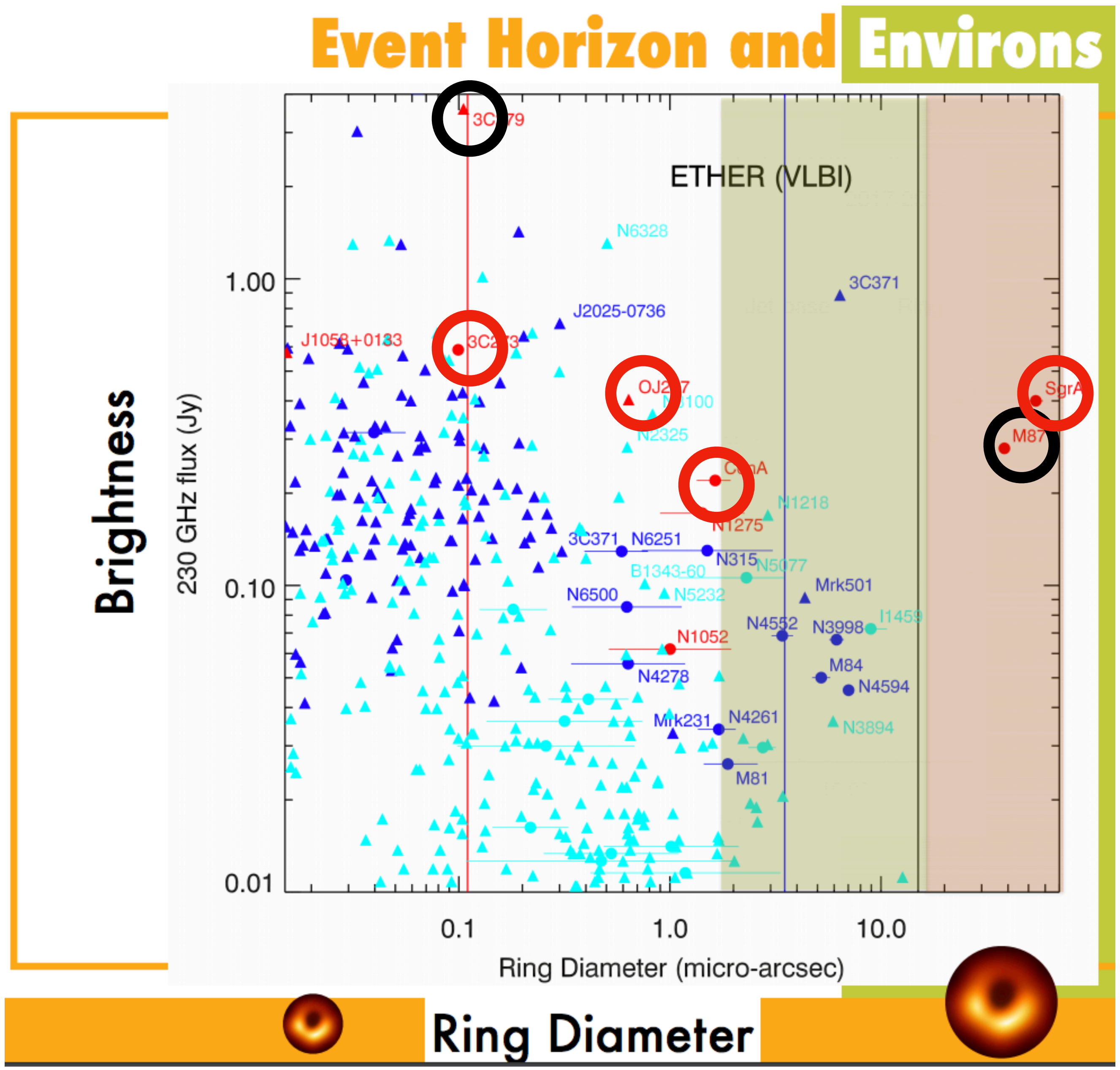


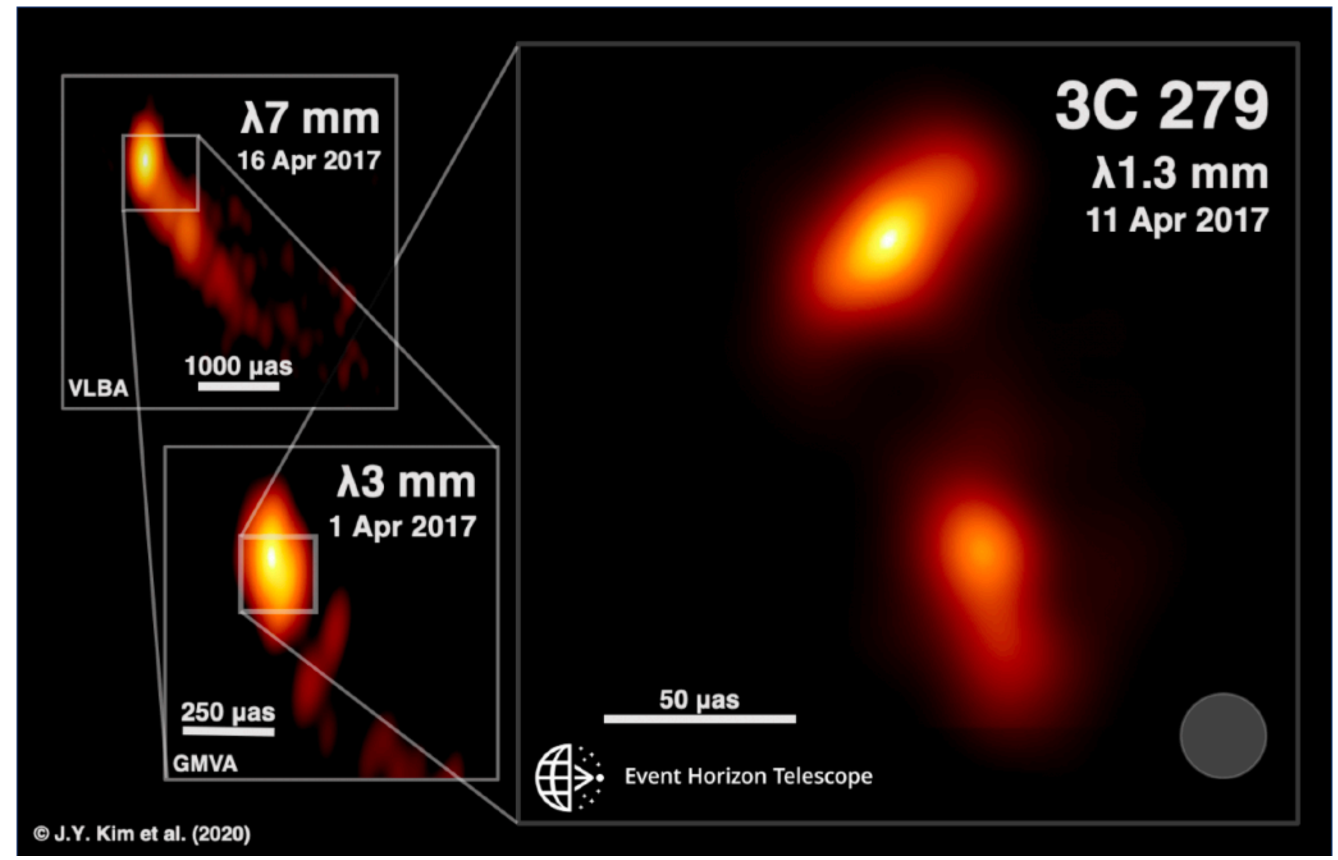

Credit: Neil Nagar




Kim, Krichbaum, Broderick, **Wielgus** + EHTC, A&A 2020

# More targets

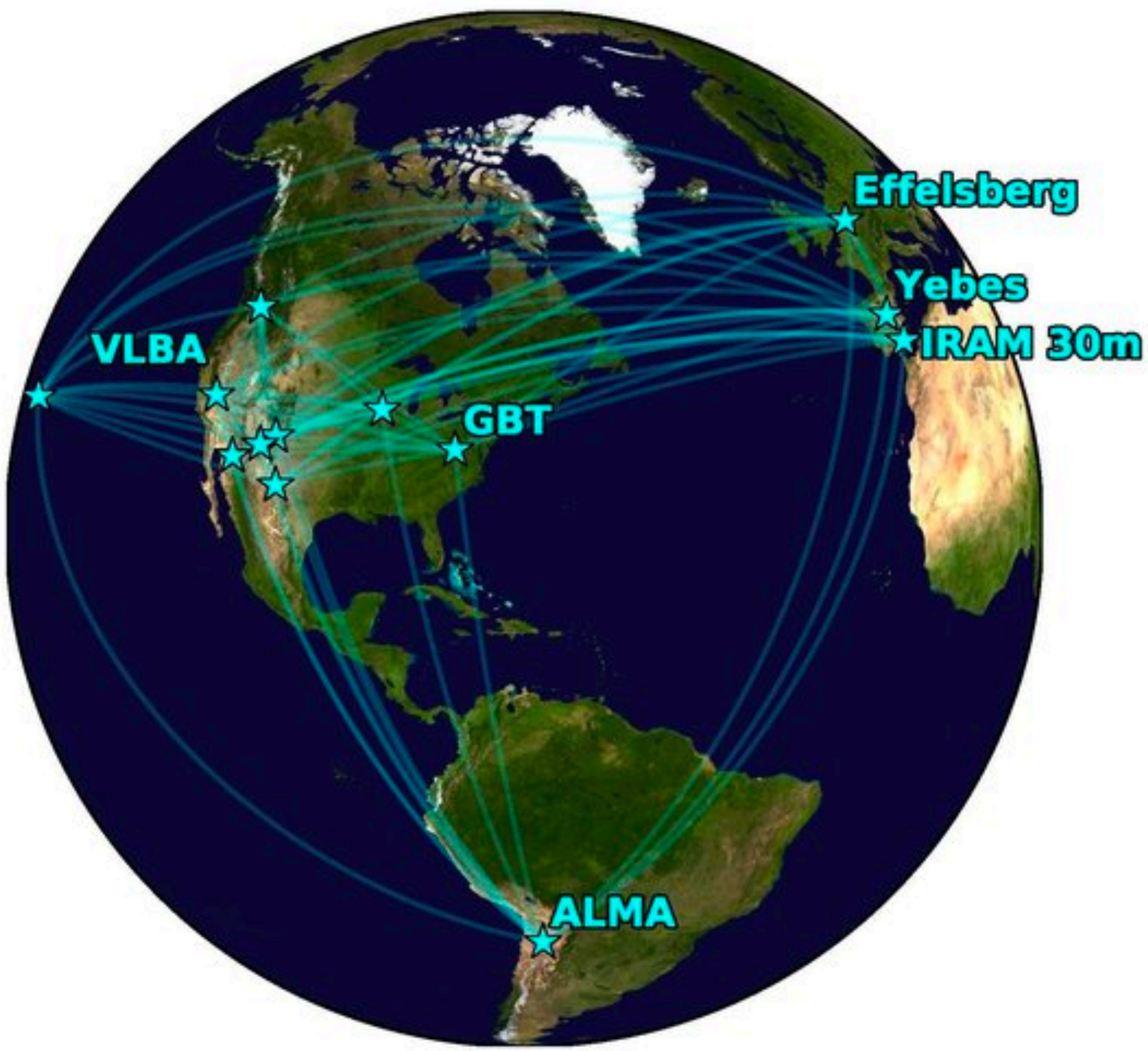


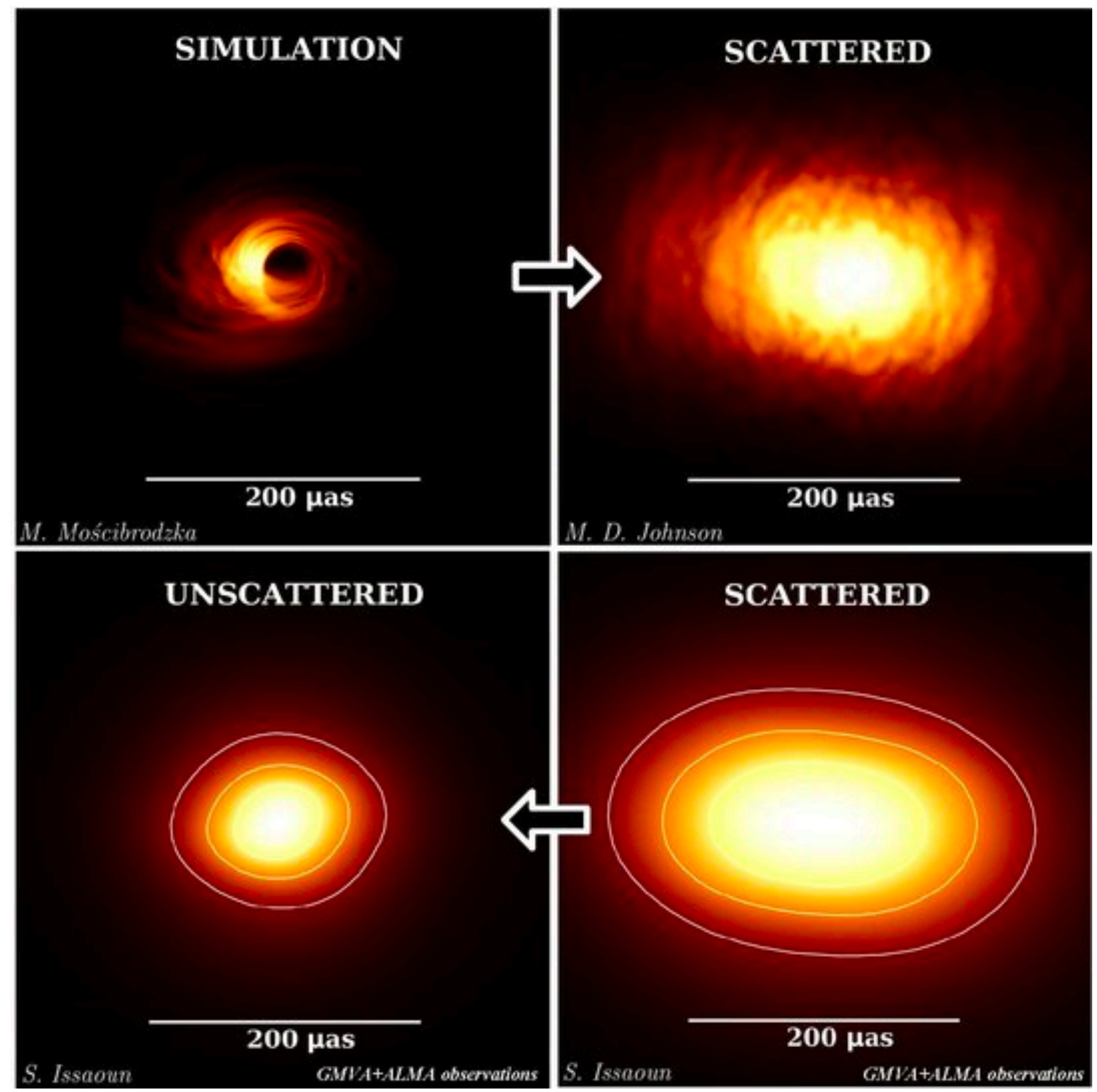

Kim, Krichbaum, Broderick, **Wielgus** + EHTC, A&A 2020

Credit: Neil Nagar

# Global Millimeter VLBI Array (GMVA)




**First intrinsic image of Sgr A* (3.5 mm)**




Issaoun et al 2019, ApJ

Global high-frequency VLBI will be pushing through the limits of technology in 2020s, delivering highest resolution images and richest quality data on accreting super massive black hole systems we have ever seen